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THE SUPERSONIC TRANSPORT - A TECHNICAL SUMMARY

By Staff of the Langley Research Center

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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THE SUPERSONIC TRANSPORT - A TECHNICAL SUMMARY

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INTRODUCTION

By John Stack

The prospects for commercial flight at supersonic speeds herald a new era in the transportation field. The successful development of a supersonic transport is of vital importance to the national prestige as well as the commercial stature of the United States. If the United States is to achieve a supersonic air transport capability at the earliest practicable date, a vigorous effort is demanded on all fronts.

A considerable amount of research background pertinent to the supersonic commercial transport has already been established as a result of the research impetus from the need for military supersonic bombardment aircraft. Concurrently with this research, the NASA has made studies of the application of this work to the commercial supersonic transport and has investigated some commercial-type configurations experimentally. While many of these configurations have serious limitations for commercial operation, reasonably clear definitions of the problem areas have been achieved and possible new approaches are under study.

The state of the art with respect to flight and propulsion efficiency of supersonic aircraft has been advanced to the point that the cruise part of the flight can now be achieved with efficiencies comparable to those of present jet transport aircraft. The vehicle configurations considered to date are essentially supersonic-type configurations and as such have serious limitations in the off-design areas, specifically: take-off, climbout, in-flight emergencies, and holding. The noise problem of the sonic boom requires subsonic operation in climbout until high altitudes are obtained. The terminal hold operation must be conducted at subsonic speeds and is very sensitive to hold altitude. One-engine-out emergency during cruise may require the availability of a midrange alternate landing site.

The technical position in terms of state of the art might be briefly summarized by saying that if the mission involved flight at only the design supersonic speed and cruising altitude, and if no emergencies occurred, intercontinental ranges of commercial interest and importance could be readily achieved. The intermediate range through which the airplane must perform to reach its supersonic cruise speed and altitude and to descend therefrom, however, imposes problems that must be solved. The research status as of today indicates that the proper solutions to the off-design problems can be provided through some form of airframe variable geometry - such as variable sweep - in combination with an advanced fan-type propulsion system. The present research position is that no fundamental problem appears with regard to these off-design conditions that cannot be solved by concentrated research effort.

I. STATE OF THE ART - PERFORMANCE

By Mark R. Nichols

One of the principal barriers to consideration of the supersonic transport has been inability of the designer to attain an adequate level of flight efficiency, that is, adequate range and an acceptable level of fuel cost. Recently, a number of advances have been made that permit more optimism concerning these problems. The purpose of this discussion is to review the performance picture briefly as background for the following presentations, and to point out some of the principal problem areas.

The major factors affecting the flight efficiency of a long-range airplane are as follows:

(1) The available energy per pound of fuel

(2) The structural weight of the airframe and engine, which determines the amount of fuel that can be carried

(3) The efficiency of the propulsion system, which is the efficiency with which the fuel is utilized in providing thrust

(4) The aerodynamic efficiency, which determines how much thrust is needed.

A high degree of efficiency is required in connection with each factor before the supersonic-cruise airplane is economically feasible. The change in overall flight efficiency with increasing flight speed, however, is determined principally by the last two factors.

Figure 1 shows the variation of propulsive efficiency with cruise Mach number for several engine types. The band on the left is for the turbojet and turbofan engines. In general, values for the various turbofan engines tend to group in the upper part of the band and those for the turbojet in the lower part; that is, the turbofan engine generally provides significantly greater efficiency than the comparable turbojet. As the flight speed increases into the region beyond a Mach number of 2, the thrust attainable with these particular engines eventually becomes insufficient to overcome the airplane's drag; therefore, it becomes necessary to add an afterburner. The efficiency then drops as indicated into the region of values covered by the middle band. As the flight speed further increases and approaches a Mach number of 4, the rapidly increasing internal-flow temperatures require elimination of the internal machinery altogether and utilization of the ramjet mode of operation. At the present time, of course, the pure ramjet is not being considered seriously for transport application. A hybrid engine, the turbo-ramjet, however, offers the possibility of efficient operation at Mach numbers in the range of about 3.5 to 5 with operating characteristics at the lower speeds similar to those for the other engine types.

In general, the propulsion efficiency attainable increases with increasing flight speed. The values corresponding to the upper parts of the three bands are as high as or higher than anything ever obtained at subsonic speeds with propeller-engine combinations.

The aerodynamic efficiency, unfortunately, has an opposite trend. In figure 2, the lift-drag ratio L/D for a number of subsonic and supersonic configurations is plotted as a function of cruise Mach number. The curves on the left are for familiar subsonic designs. Above a Mach number of 1, the lowest curve shown is representative of the approximate performance of present-day operational supersonic airplanes. It can be seen that a drastic decrease in L/D occurs at transonic speeds in connection with the development of supersonic flow around the airplane. The supersonic lift-drag ratio of the typical present-day supersonic design is, for example, only about one-fourth of that for the subsonic design at a Mach number of 0.8. This decrease makes the aerodynamic efficiency the critical factor. As a result, much research effort has been concentrated on lift-drag ratio and has resulted in an increase of the values obtained by 50 to 75 percent in the last 3 years. The plotted test points in figure 2 identify values established by wind-tunnel model tests of military configurations designed for supersonic missions. It is estimated that if these arrangements were converted into transport configurations, through an increase in fuselage size, etc., the corresponding lift-drag ratios would fall approximately in the shaded band. Analysis indicates that these new state-of-the-art values are high enough to provide useful performance, but are still not as high as the designer would like. It is essential, therefore, that a vigorous research program be continued to provide further design improvements.

The manner in which the propulsion and lift-drag-ratio trends tend to compensate in the overall flight efficiency picture is shown in figure 3. The flight efficiency is plotted against the design cruise Mach number. The shaded region on the left indicates the approximate level of efficiency of the present jet transports, whereas the second shaded region indicates the best present estimate of efficiency at supersonic speeds. It will be noted that the supersonic values are not quite as high as the subsonic values, which, of course, are subject to further improvement. Nevertheless, they are competitive, and a number of analyses show that the gain in earning power generated by the increased speed of the supersonic airplane far more than compensates for a difference in efficiency of the magnitude shown. In other words, an airplane designed to cruise at a Mach number of 3 can make approximately three times as many trans-Atlantic trips a day as one of the present-day jets. When all other factors are assumed equal, these trips can then gross three times as much money, and thus some difference in fuel costs can be tolerated.

At the present time research and analysis have not defined exactly what cruise Mach number is optimum for a given mission, or even which configuration is optimum for any particular design speed. The best arrangement might be like one of the sketches at the top of figure 3, or like one of the display models shown in figures 4 to 6. A Mach number 3 cruise speed and the delta-wing canard arrangement of figure 4, however, have been chosen for further study of some of the operational characteristics of the supersonic transport. The reason for this choice of configuration is that it is the one for which most data exist and the one most widely accepted presently.

The airplane illustrated in figure 7 is a large transport designed to cruise at a Mach number of 3 and to carry 100 passengers and a crew of 6. It weighs about 375,000 pounds, is about 180 feet long, and has a total surface area of about one-third of an acre. The fuel, which constitutes about 55 percent of the take-off weight, is located in both the wing and fuselage in the cross-hatched regions. The fuselage also is heavily insulated and extensively air-conditioned because the surface temperatures vary from 400° to 650°. This temperature problem and associated structural considerations are discussed in other parts of this volume.

In order to attain the level of flight efficiencies assumed, two major requirements must be met. First, the entire surface area (about one-third of an acre) must be very smooth and fair with no sand-grain-type roughness or offsets between adjacent structural panels higher than about three times the thickness of a sheet of tablet paper. Second, the overall configuration must be very slender. The wing of the configuration illustrated is only slightly thicker in proportion than a razor blade. The fuselage diameter also is small relative to its length and thus leads to a seating arrangement as compact as most present-day coach seatings. It is assumed that such dense seating will be permissible for the supersonic transport because of the very short flight times.

Figure 8 shows a flight plan for this transport that has been made optimum on the New York to Paris route primarily on a minimum-fuel-consumption basis. Altitude in thousands of feet is plotted against distance in nautical miles with the horizontal scale broken in two places. The airplane utilizes 1 minute of full afterburner at take-off and then climbs at high subsonic speeds with normal rated power. When the rate of climb begins to drop off unduly (in this case, at 25,000 feet), the afterburner is turned on, so that the airplane accelerates through sonic speed and then continues to climb and accelerate to its initial cruise condition of Mach number 3 at 65,000 feet. Over one-third of the total fuel aboard at take-off is consumed in this phase of the flight which takes half an hour and covers 365 nautical miles. The major problem areas appear to be: (1) high fuel consumption in off-design flight; (2) long take-off distances and high take-off speeds; and finally, (3) public reaction to afterburner take-offs and intense sonic bangs generated in the transonic acceleration. These problems are treated in greater detail in subsequent parts of this volume.

The airplane cruises at Mach number 3 with reduced afterburner temperature for about $1\frac{1}{2}$ hours with the flight altitude increasing gradually to 73,000 feet as fuel is burned. These flight altitudes are optimums determined on the basis of a compromise between conflicting airframe and engine efficiency trends. If the altitude is increased beyond the optimum, the fuel consumption goes up rapidly because higher afterburner temperatures are needed. Conversely, reducing the flight altitude causes losses in lift-drag ratio which, of course, reflect in increased thrust requirements. Thus, the operating economy of the airplane will depend to an unprecedented extent on the way to which the airplane is permitted to operate by the airways control system.

One other significant area of new operating problems arises in the cruise phase of the flight because of the inability of the airplane to be slowed rapidly from cruise Mach number to subsonic speeds in case of an emergency or in order to minimize the effects of rough air.

Letdown is initiated at the end of cruise by throttling the engines to the minimum operating thrust and then decelerating at the glide angle for maximum range. The airplane decelerates through the sonic speed at an altitude of 59,000 feet so that there is no major ground noise problem. The time required and distance covered during descent are about the same as for the initial leg of the flight, but the fuel usage is, of course, very much less. Landing speeds and distances, however, are expected to be somewhat higher than for the present jets.

The total flight time is about $2\frac{1}{2}$ hours and the fuel cost per passenger is only a little more than that for present subsonic jets. Thus, as indicated before, the future of these airplanes appears bright.

One overall problem of major importance is that the flight plan is very rigid and the fuel consumption is high, so that any off-design flight is very expensive. For example, just changing hold altitude from the 35,000-foot value illustrated to 5,000 feet requires an increase in fuel reserve of 1 ton, which effectively eliminates approximately 12 passengers if this weight is taken out of the payload. Other changes are equally expensive. It is quite apparent that not many such changes can be tolerated.

In summary, it now appears that the state of the art has advanced sufficiently to permit the design of an airplane at least marginally capable of performing the supersonic transport mission. Most designs proposed so far, however, appear to have serious shortcomings with regard to off-design performance and operational flexibility. Additional changes to both the basic airframe and engine configurations, along the lines that will be discussed subsequently, appear desirable to overcome these adverse characteristics. Another thing obviously needed is a system of flight controls, communications, and meteorology good enough to enable the airplane to fly in an optimum manner at all times. Ideally, the flight would be planned to the minute with all air space and landing pattern reservations made prior to the time the engines are started.

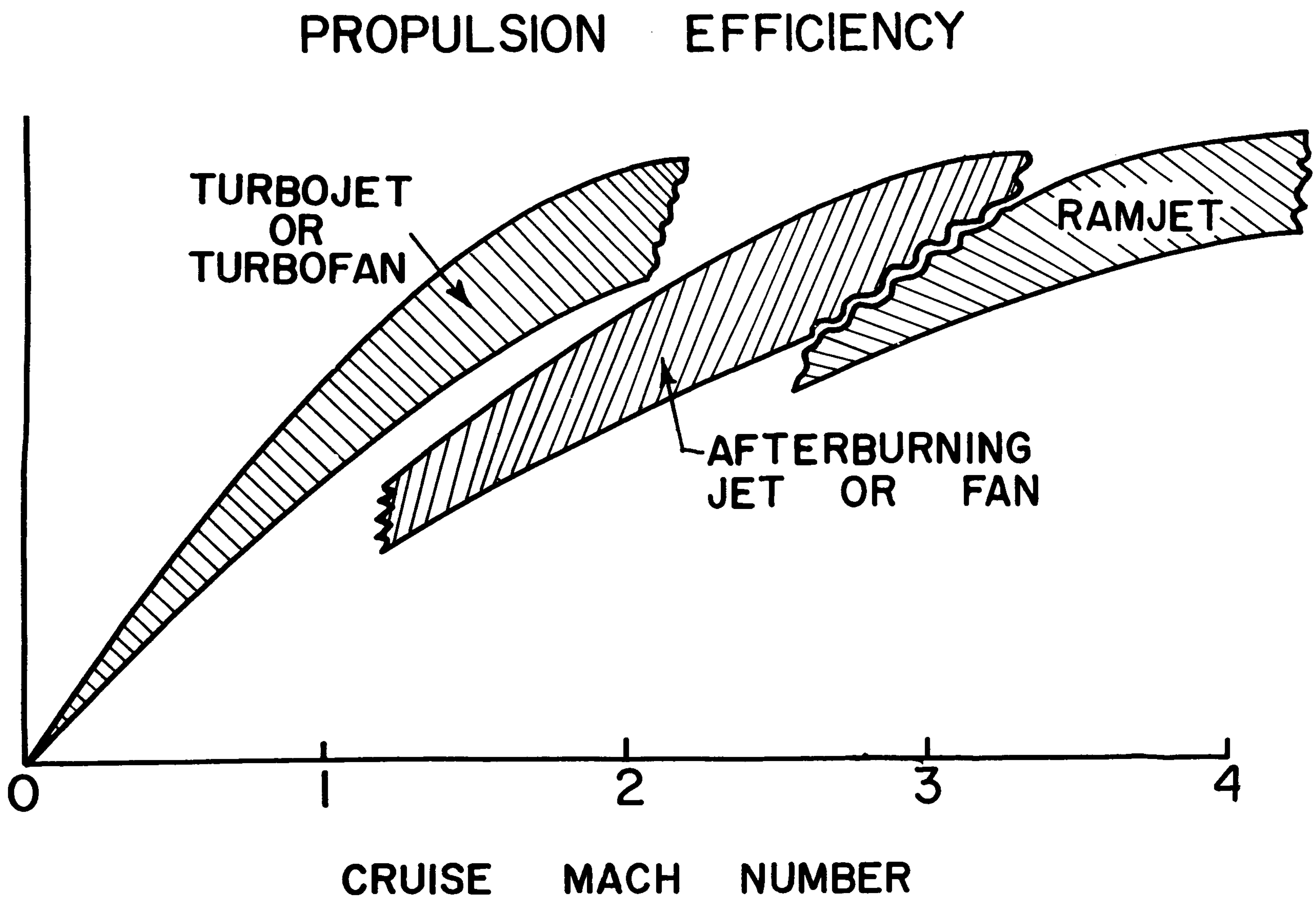
PROPULSION EFFICIENCY
TURBOJET OR TURBOFAN
AFTERBURNING JET OR FAN
RAMJET
0
1
2
3
4
CRUISE MACH NUMBER

Figure 1

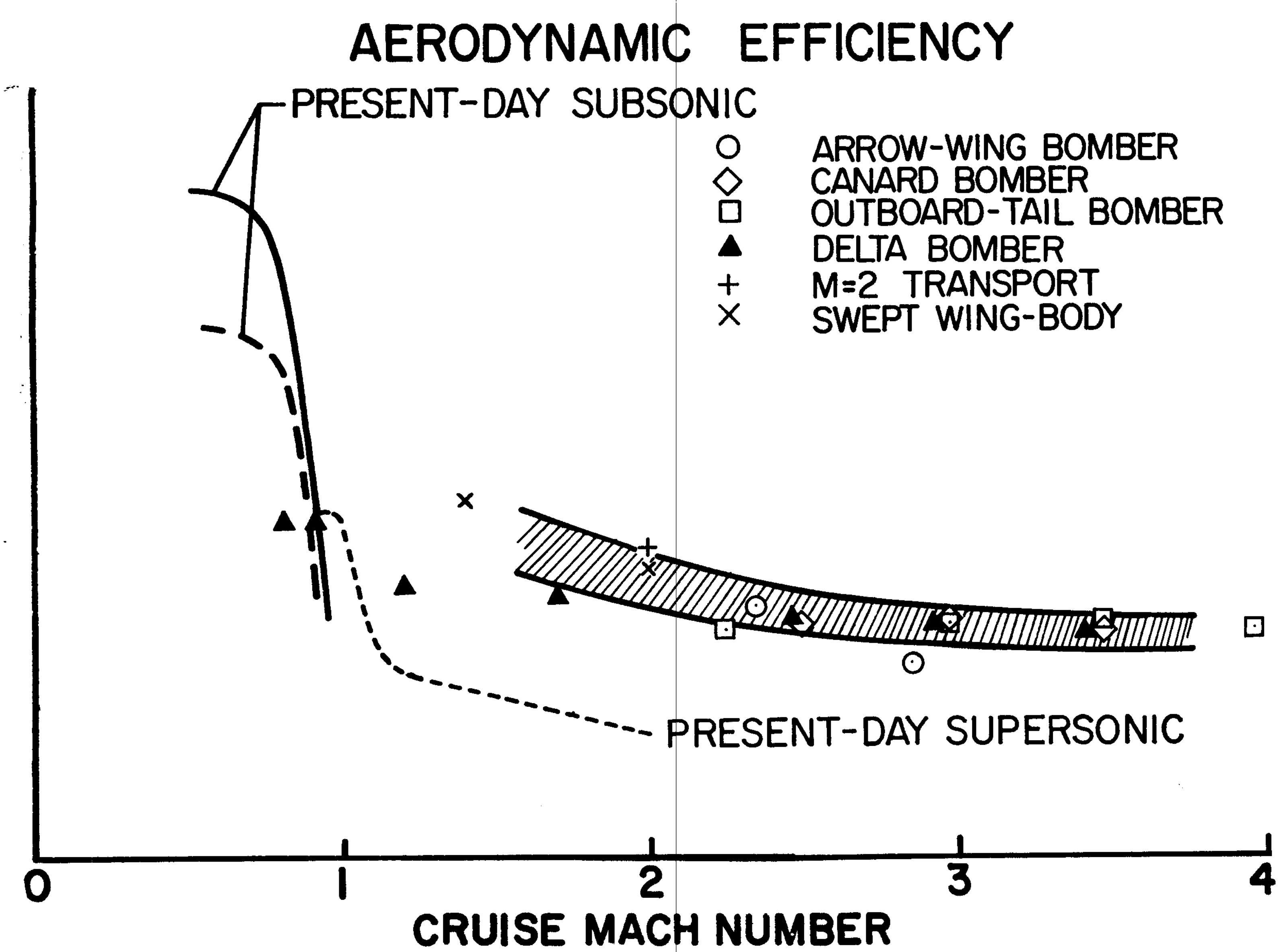
AERODYNAMIC EFFICIENCY
PRESENT-DAY SUBSONIC
ARROW-WING BOMBER
CANARD BOMBER
OUTBOARD-TAIL BOMBER
DELTA BOMBER
M=2 TRANSPORT
SWEPT WING-BODY
PRESENT-DAY SUPERSONIC
0
1
2
3
4
CRUISE MACH NUMBER

Figure 2

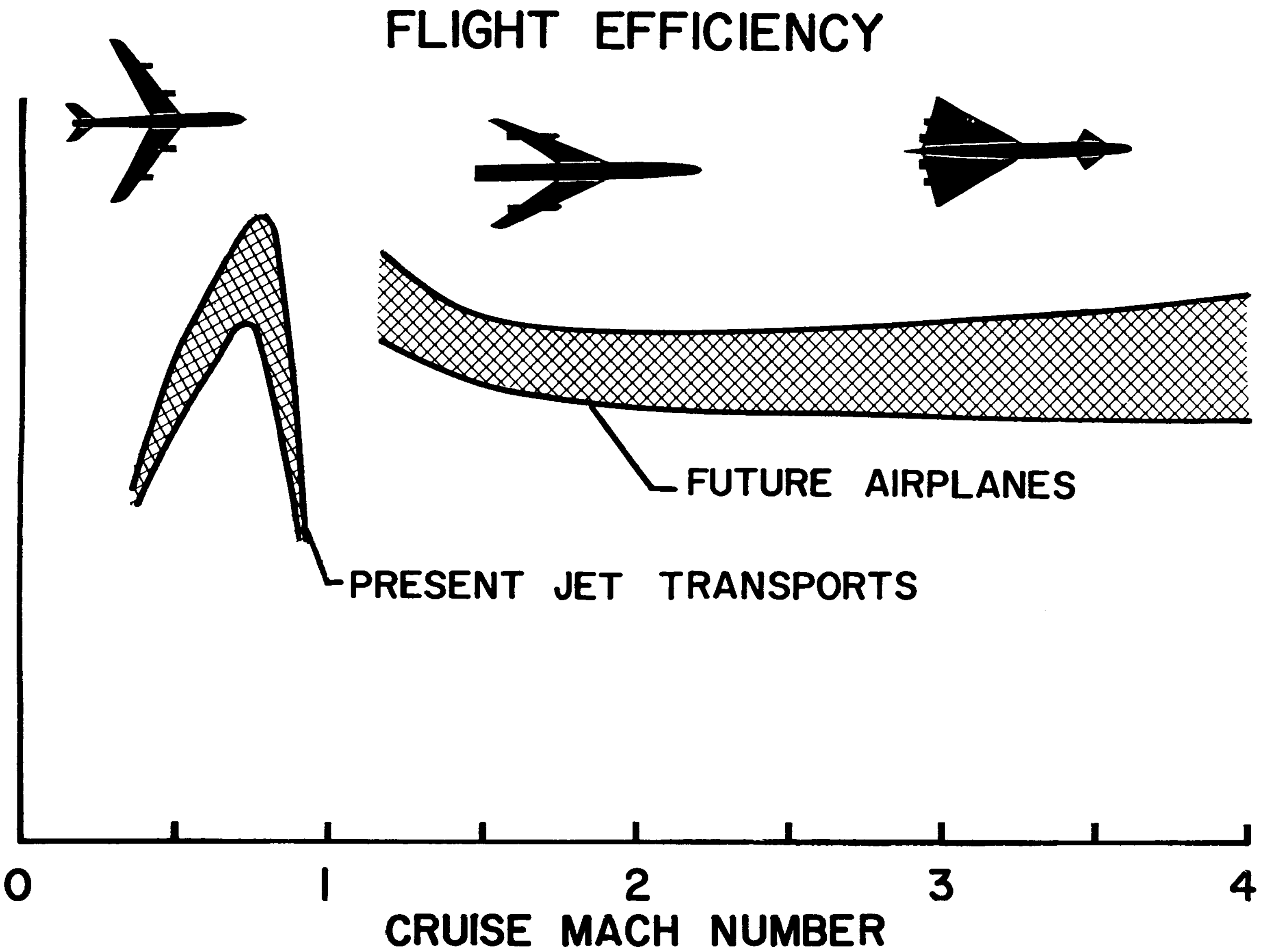
FLIGHT EFFICIENCY
FUTURE AIRPLANES
PRESENT JET TRANSPORTS
0
1
2
3
4
CRUISE MACH NUMBER

Figure 3

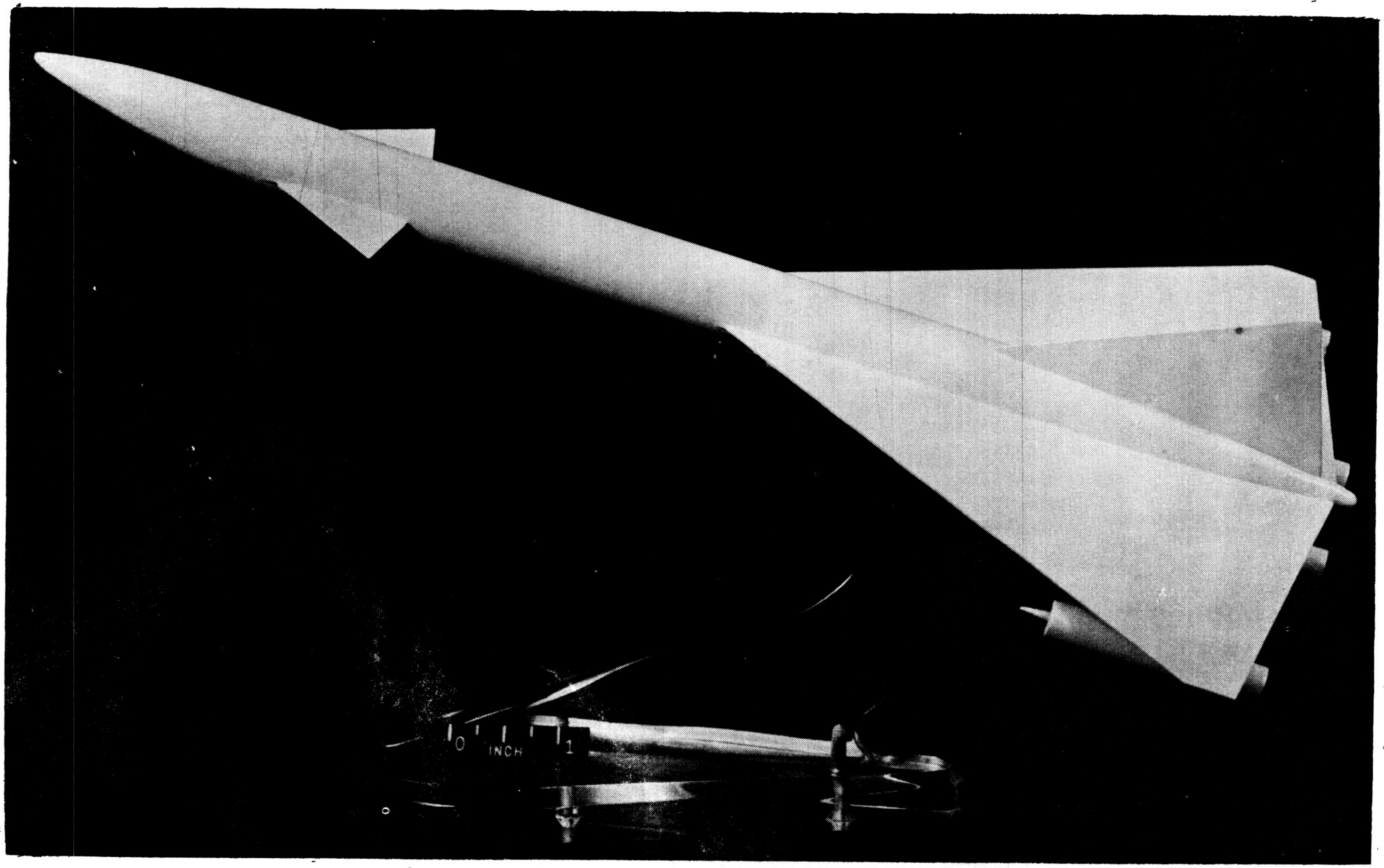

Figure 4.- Delta canard supersonic transport. L-59-8566

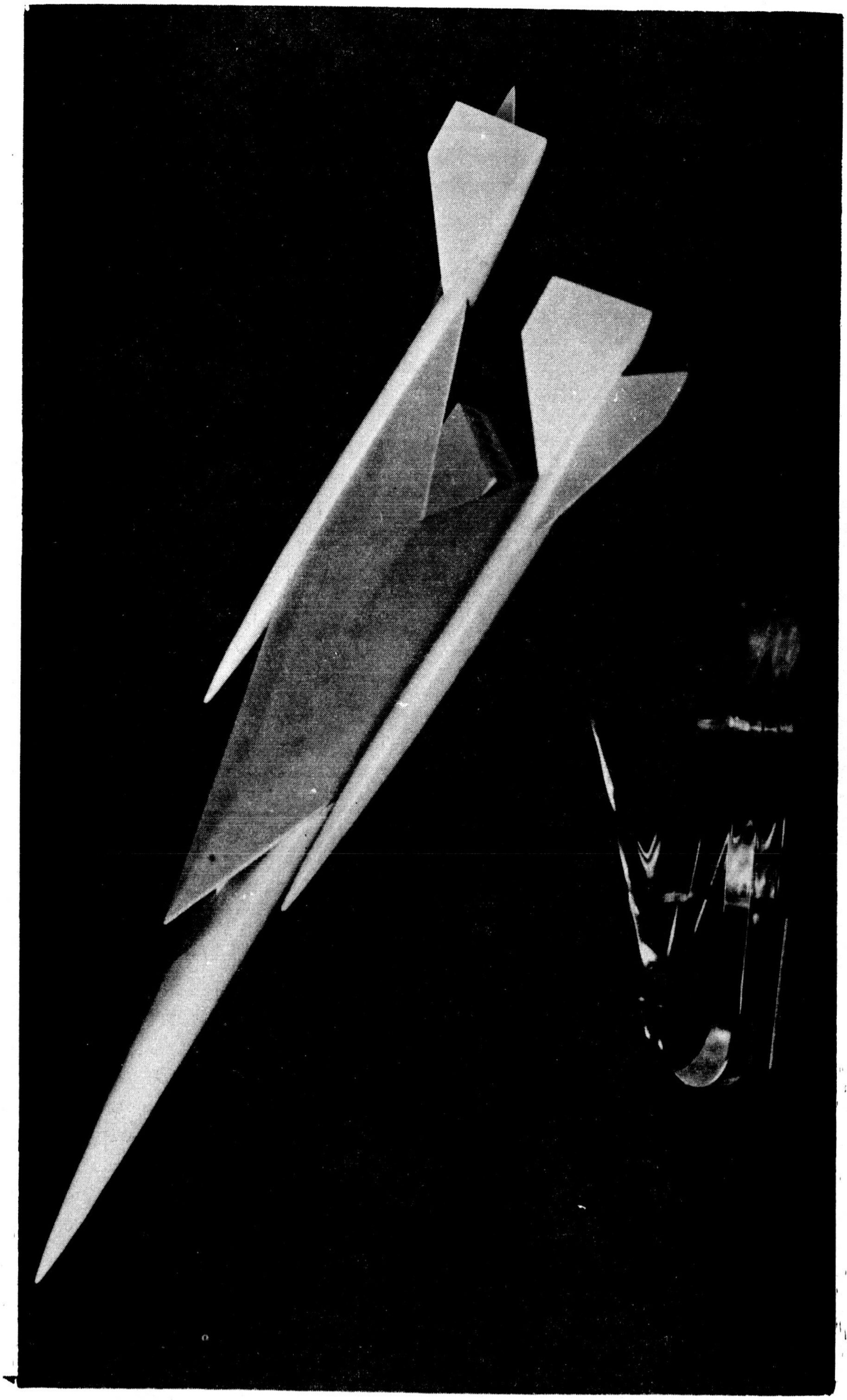

Figure 5.- Outboard-tail supersonic transport. L-59-8565

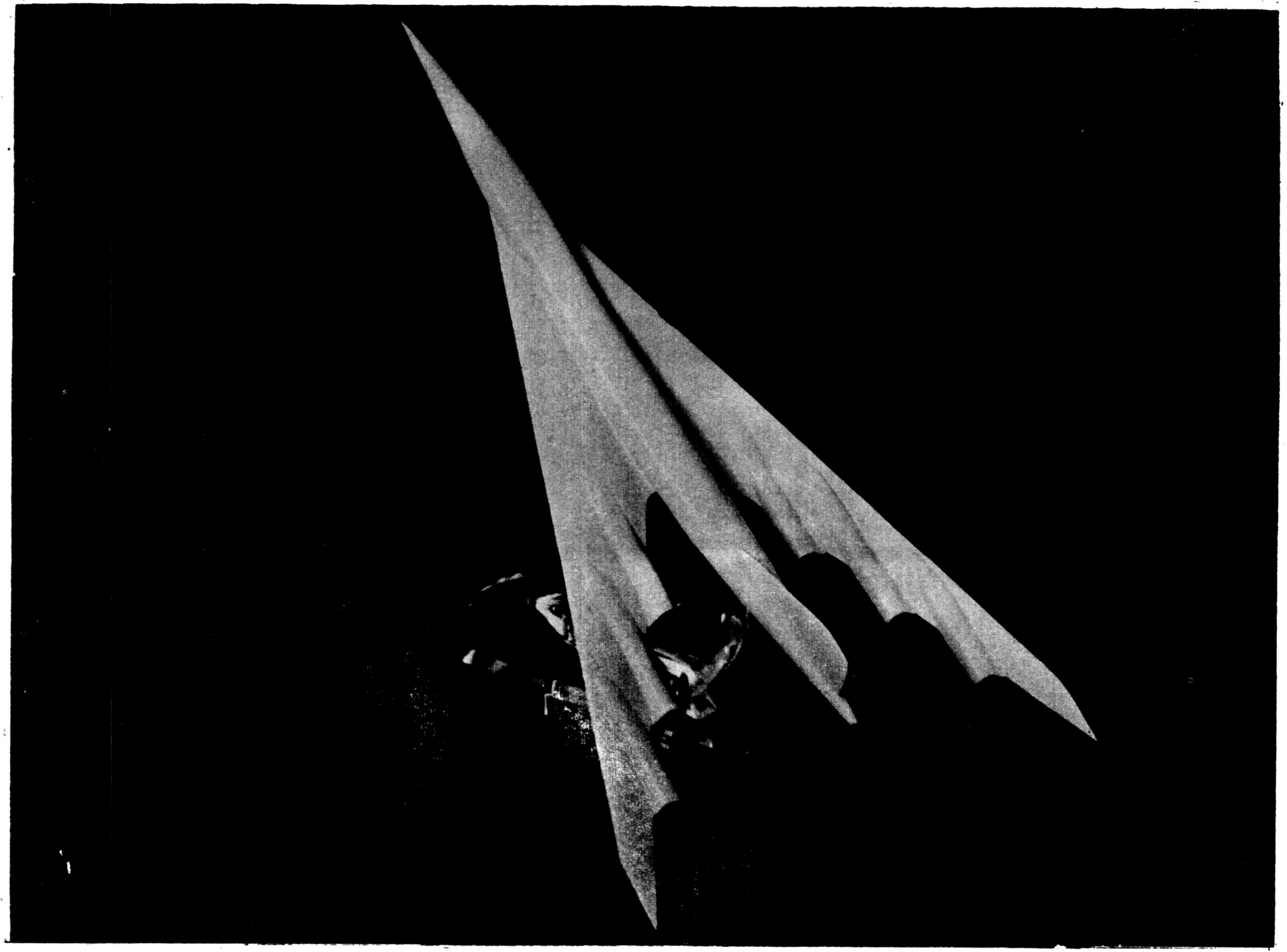

Figure 6.- Swept-wing supersonic transport. L-59-8567

M = 3 TRANSPORT

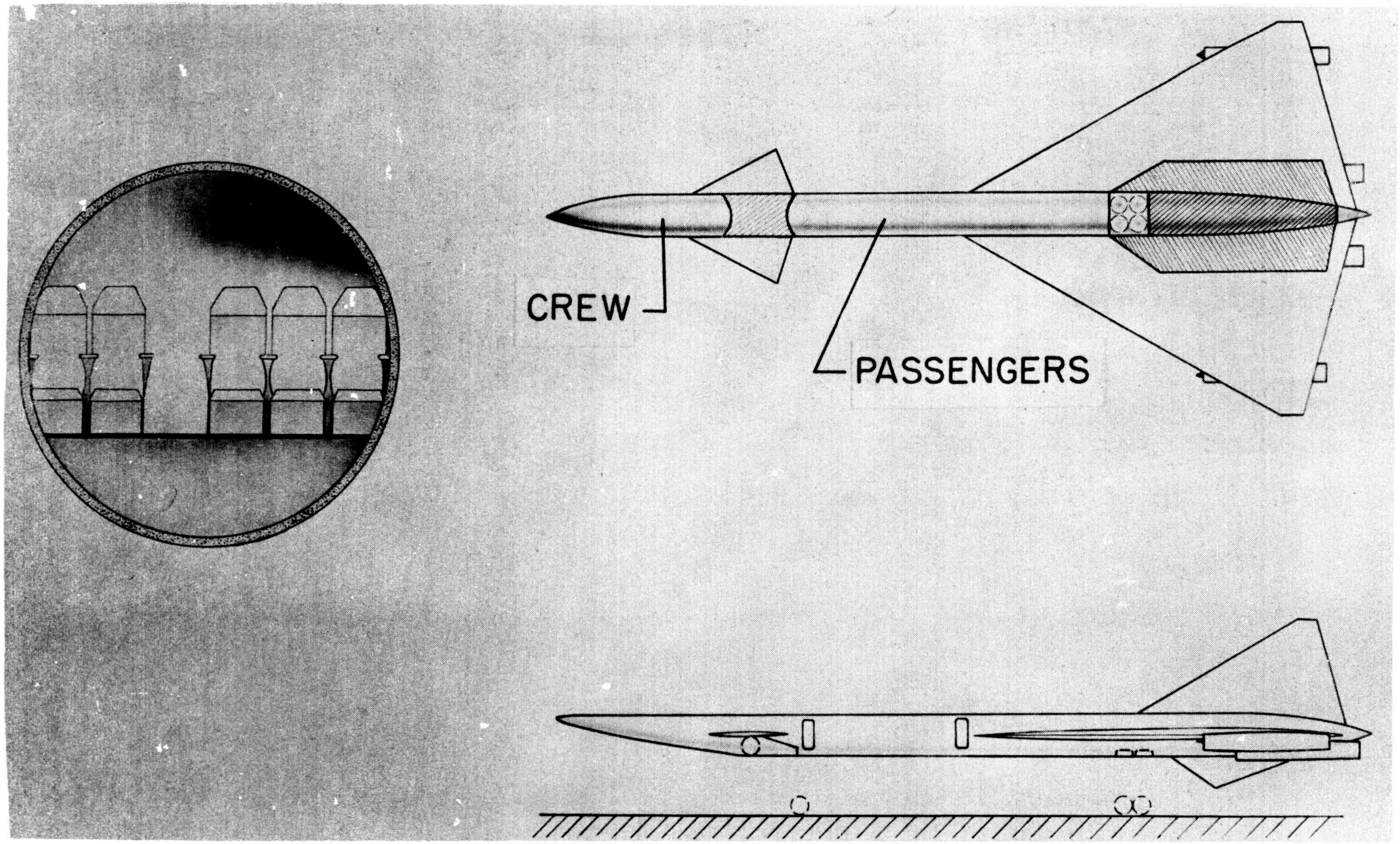

Figure 7

NEW YORK-PARIS FLIGHT PLAN

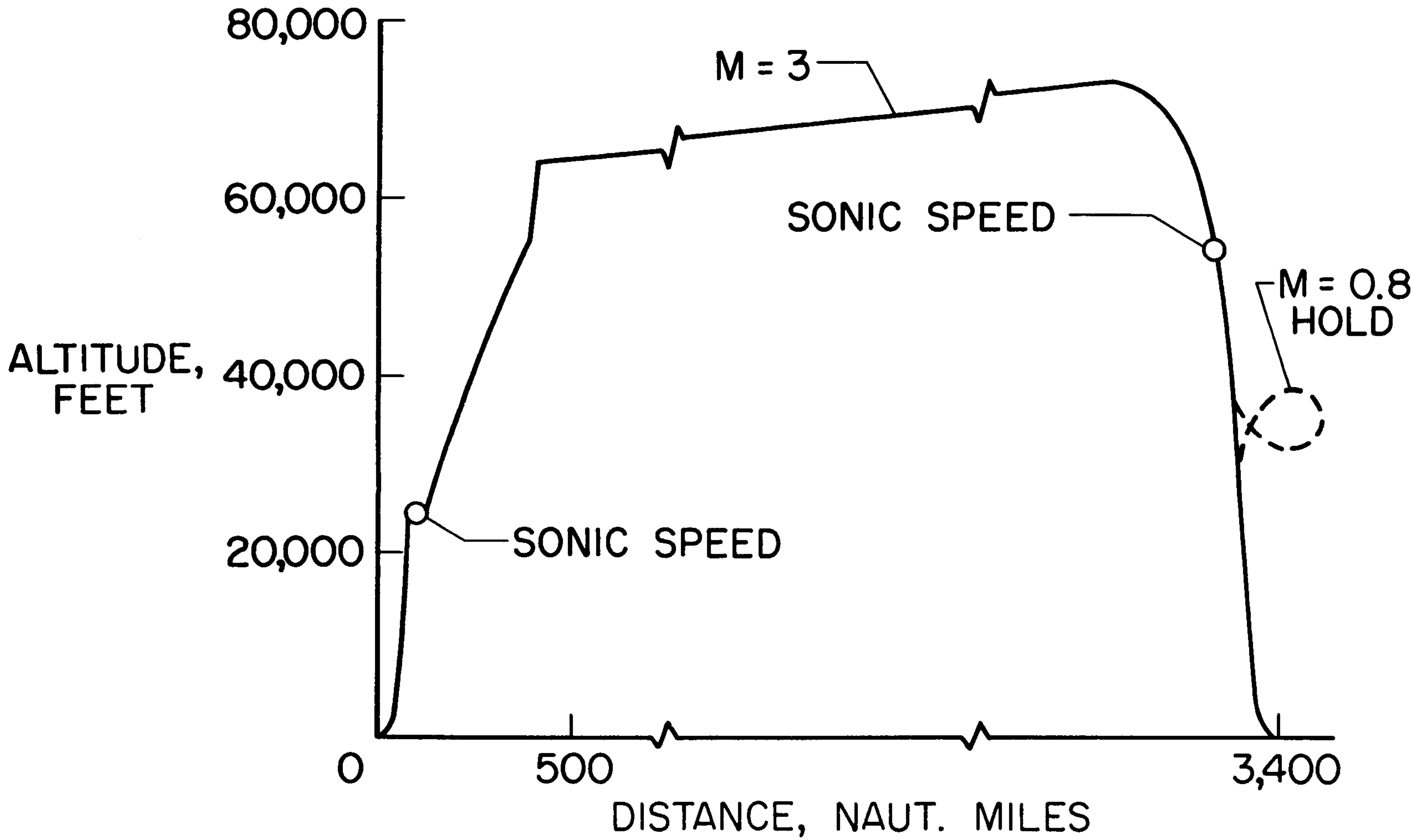

Figure 8

II. SOME NOISE PROBLEMS OF THE SUPERSONIC TRANSPORT

By Harvey H. Hubbard and Domenic J. Maglieri

INTRODUCTION

The noise problems of the supersonic transport airplane can be discussed with the aid of table I. At the left of this table are indicated the main sources of noise during airplane operation. These sources are noted to be the engines, the aerodynamic boundary layer, and the shock waves. Across the top of this table are listed the various phases of operation of the aircraft, such as ground runup, take-off, initial climb, acceleration, cruise, descent, and landing approach. In the central portion of the table, the problem areas are related to the sources of the noise and the phases of airplane operation. With regard to engine noise, a rather general observation can be made that the problems will be similar in nature to those encountered in present-day jet transport operation. The seriousness of these engine noise problems will, of course, depend on the type of power plant, the aircraft configuration, and the manner in which the aircraft is operated. The boundary-layer noise will definitely be of greater concern for the supersonic transport, and the shock waves are an entirely new source of noise which is generated by the aircraft only in supersonic flight.

ENGINE NOISE

The possible problem areas associated with engine operation include the fatigue damage to the aircraft structure during ground runups and take-off (ref. 1), harmful exposure of the ground crew and other people on the ground during ground runups (ref. 2), and objectionable noise on the ground in communities near airports for both the initial climb and the landing approach (ref. 3). At present, in the operation of subsonic turbojet-powered transports, both ground mufflers and flight mufflers are needed. Mufflers serve a twofold purpose. Ground mufflers reduce damage to the structure and give protection to the ground crews. Flight mufflers reduce community annoyance and also reduce damage to the structure. The use of turbofan-type engines will probably eliminate the need for flight-type jet exhaust mufflers although ground-runup jet exhaust mufflers would still be required.

Of particular significance in the community noise problem is the climbout capability of the aircraft. This can be illustrated with the aid of figure 1, which shows schematically the altitude in feet, achieved as a function of ground distance in miles from point of lift-off, for both a subsonic and a proposed supersonic transport. It is obvious that the supersonic airplane will have the steeper climb angle. This results from the fact that engines capable of propelling the aircraft in supersonic flight will have greater than the minimum thrust required for take-off. This excess take-off thrust, combined with the possible use of variable aircraft wing geometry, will make possible geometric climbout angles of the order of 10°, or about double those being used at present. This improved climbout capability of the supersonic transport will allow it to attain a greater altitude in a given ground distance. For given engine noise characteristics, this increased altitude is very beneficial in reducing community annoyance.

The noise characteristics of future engines will no doubt differ from those in current use. Several possible engines have been proposed for use in the supersonic transport, and their merits are still being debated. Since noise measurements are not available for these proposed engines, estimates have been made of their noise characteristics, and the main results of these studies are shown in figure 2. Noise levels are plotted on the vertical scale as a function of horizontal distance in miles from the point of lift-off. The noise data are presented in the form of perceived noise levels (PNdb) since this quantity has been found to be a fairly realistic measure of community reaction. The horizontal line in the center of the chart corresponds to 112 PNdb which has been judged to be an acceptable noise level in communities for daylight and early evening take-off operations. Note that levels below the line are considered acceptable, whereas levels above the line are not acceptable. The two dashed curves represent the extreme values of perceived noise levels calculated for a four-engine supersonic aircraft having a total of 120,000 pounds thrust and climbing at an angle of 10°. The top dashed curve is calculated for full afterburning-type engines whereas the lower dashed curve is calculated for turbofan-type engines. Nonafterburning unsuppressed turbojet engines of equivalent thrust would have perceived noise levels between these two extremes. As a basis for comparison, the shaded area is included to represent the ranges of perceived noise levels encountered during operations of four-engine subsonic jet transports with suppressors, having a total thrust of 48,000 pounds and climbing at a 5° angle (ref. 3). The range of perceived noise levels of the shaded region accounts for differences in airplane gross weights and the associated variation in engine power settings. The main objective is to operate in such a way that the perceived noise levels on the ground become equal to or less than this acceptable level in as short a ground distance as possible.

It is obvious from the data of figure 2 that the noise characteristics of these engines that have been proposed for the supersonic transport vary widely. If proper consideration is not given for the community annoyance problem, a power plant might be chosen that would have unacceptable noise characteristics. On the other hand, the possibility exists of choosing a power plant that would be, from consideration of community annoyance, better than those currently in use.

BOUNDARY-LAYER NOISE

For present subsonic jet transports, the boundary-layer noise is mainly of concern from the standpoint of passenger comfort, and as a result several thousand pounds of sound-treatment materials are needed in the fuselage. On supersonic transports the boundary-layer noise pressures will be higher and will be of concern not only from the standpoint of passenger comfort, but also because of possible noise-induced damage to the skin structure of the airplane.

The boundary-layer noise problem, as it relates to supersonic transports, can be discussed with the aid of figure 3. A laminar boundary layer is present at the front of the aircraft, as indicated by the unshaded part of the sketch at the top of the figure. The transition to turbulent boundary layer occurs at a short distance back along the fuselage where the shading starts, and this turbulent boundary layer thickens up toward the rear of the aircraft as indicated by the darker shading. In both the subsonic and supersonic Mach number ranges the boundary-layer noise frequencies are noted to decrease as the boundary layer thickens, and hence there is a substantial change in the spectrum from front to rear along the aircraft (refs. 4 and 5). The plot at the bottom of figure 3 presents surface-pressure levels in decibels as a function of distance along the fuselage measured from the nose of the aircraft. The crosshatched region represents the range of surface-pressure levels estimated for a supersonic transport operating in the Mach number range 2.3 to 4.0 and at altitudes of 60,000 to 70,000 feet. The surface pressures are of low intensity in the laminar boundary-layer region, increase suddenly in the region of transition, and then vary only a small amount in the turbulent boundary-layer region, with the exception of some pressure buildups in regions of separated flow as may exist near the rear of the fuselage. Shown in the figure for comparison are the surface-pressure levels estimated for the cruise condition of a subsonic transport operating in the Mach number range 0.8 to 0.9 and at altitudes of 25,000 to 35,000 feet. The free-stream dynamic pressure corresponding to the operation of the subsonic jet transport is about 250 to 500 lb/sq ft, whereas the corresponding dynamic pressure during the cruise of the supersonic transport is in the range from 750 to 1,250 lb/sq ft. The surface pressures in the boundary layer are approximately proportional to the free-stream dynamic pressure, and as a result the surface-pressure levels will be substantially higher for the supersonic transport.

The resulting surface-pressure levels of the supersonic transport are significant because they are in a range where noise-induced structural damage can occur (ref. 6). Thus, in addition to an intensification of the familiar problem of providing optimum sound insulation for the passengers, there is also concern for the design of a skin structure to resist noise-induced damage over the whole area of the aircraft indicated by the shading in the sketch. (See fig. 3.) Possible structural damage due to boundary-layer noise imposes a much more severe requirement in design than for current jet transport aircraft.

SHOCK-WAVE NOISE

Additional sources of noise in the operation of a supersonic transport, which are not a problem with subsonic transports, are the shock waves generated during the supersonic part of the flight which includes the climb, cruise, and descent. Although the resulting sonic-boom disturbances may be observed throughout these phases of the flight, the most serious problems are associated with the acceleration during climb since this may be accomplished at a reduced flight altitude. If proper precautions are not taken, shock-wave noise pressures may be of sufficient intensity to damage parts of ground building structures such as windows, in addition to causing annoyance.

Figure 4 suggests two approaches to solving the acceleration problem: one a level-flight acceleration and the other an acceleration in steep climb (ref. 7). Airplane flight Mach number is plotted on the horizontal scale and airplane altitude on the vertical scale. The hatched area represents combinations of Mach number and altitude which may result in damage to structures on the ground. The shaded area toward the top represents combinations of Mach number and altitude for which sonic booms will be observed on the ground and which may be annoying but will not cause damage. The main objective in the flight operation is to travel from ground level to cruise conditions without intersecting the damage area. NASA flight studies have shown that increasing altitude is a very powerful factor in reducing the sonic-boom intensity. This leads to the proposed procedure illustrated in the left-hand side of figure 4. This consists of a subsonic climb to relatively high intermediate altitude, then a level-flight acceleration to a Mach number of about 2, and then a subsequent climb and acceleration to cruise condition. Note that in figure 4, 35,000 feet is the minimum acceptable altitude for a level-flight acceleration to avoid ground damage; a higher altitude than 35,000 feet is highly desirable to minimize adverse community reaction and to lessen further the possibility of ground damage.

Another possible procedure to avoid damage on the ground during the acceleration phase of the flight is illustrated in the right-hand side of figure 4. Flight tests have indicated that if a sufficient thrust-to-weight ratio is available, a steep climb may be used to advantage to reduce the sonic-boom disturbances at ground level. The benefits are derived principally from the fact that the whole shock-wave pattern is rotated by about the same amount as the airplane attitude is changed. The net result of this change in attitude of the shock-wave pattern is to allow a higher Mach number to be reached before the shock waves reach the ground. As a result, the damage area is now shifted to the right, that is, to higher Mach numbers. As an example, this shift may be in the neighborhood of 0.2 to 0.4 in Mach number, depending on altitude, for a climb angle of 20°. It can be seen from the figure that acceleration to supersonic speeds can now be accomplished at a lower altitude without intersecting the damage region providing, of course, that the aircraft remains in a climb attitude.

The results of recent NASA studies have suggested that the low Mach number part of the damage-area boundary, as represented by the dashed line in figure 4, is unstable and is sensitive to atmospheric wind and temperature gradients. The high Mach number part of the damage-area boundary, as represented by the solid line, was noted to be relatively stable and is not very sensitive to changes in the atmospheric conditions. These results suggest that the most reliable flight procedure to avoid the damage area is the one shown in the left-hand side of figure 4 since the nearest approach to the damage region occurs where its boundary is most stable. On the other hand, the steep-climb procedure involves a close approach to the damage area in the region where its boundary is unstable. The implications here are that atmospheric conditions such as strong tail winds and/or temperature inversions might tend to neutralize any benefits attained as a result of the steep-climb procedure. Atmospheric variations would present no problem in the level-flight acceleration procedure.

For a given size airplane, only small benefits would be gained from changing its shape to reduce the boom intensities. Thus, the practical solution to the sonic-boom problem lies in the manner of operation of the aircraft. With regard to aircraft operation, two additional statements can be made. Deceleration from cruise speed should be made at as high an altitude as possible, and steep descent angles at supersonic speeds should be avoided. Any radical departures from steady-level flight conditions during any of the supersonic portions of the flight should also be avoided since these may lead to intense sonic booms over localized areas on the ground.

CONCLUDING REMARKS

From a summary of the engine, boundary layer, and shock-wave noise problems, it is obvious that noise considerations will have an important bearing on the choice of the structure, the power plant, the aerodynamic configuration, and the operating practices. These noise problems should thus be considered early in the design stage of the airplane since the means for solutions to these problems will need to be integrated closely into the overall design of the airplane.

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TABLE I

SUPERSONIC TRANSPORT NOISE PROBLEMS

Noise sources	Phases of operation				
	Ground runup	Take-off	Initial climb	Acceleration, cruise, descent	Landing approach
Engines	Structure Ground Crew	Structure	Community		Community
Boundary layer				Structure Passenger Flight Crew	
Shock waves				Community	

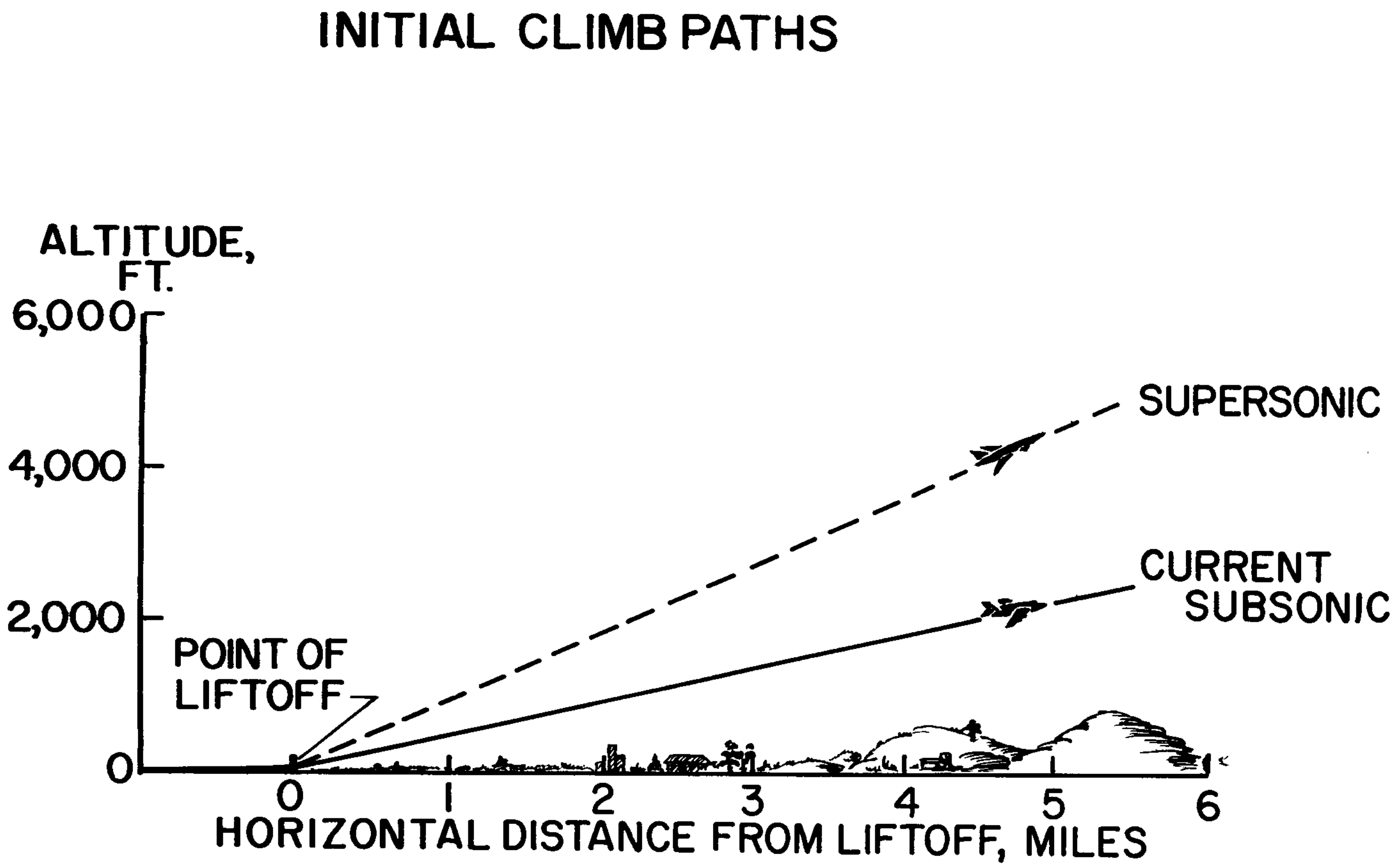
INITIAL CLIMB PATHS
ALTITUDE, FT.
6,000
4,000
2,000
0
POINT OF LIFTOFF
SUPERSONIC
CURRENT SUBSONIC
0
1
2
3
4
5
6
HORIZONTAL DISTANCE FROM LIFTOFF, MILES

Figure 1

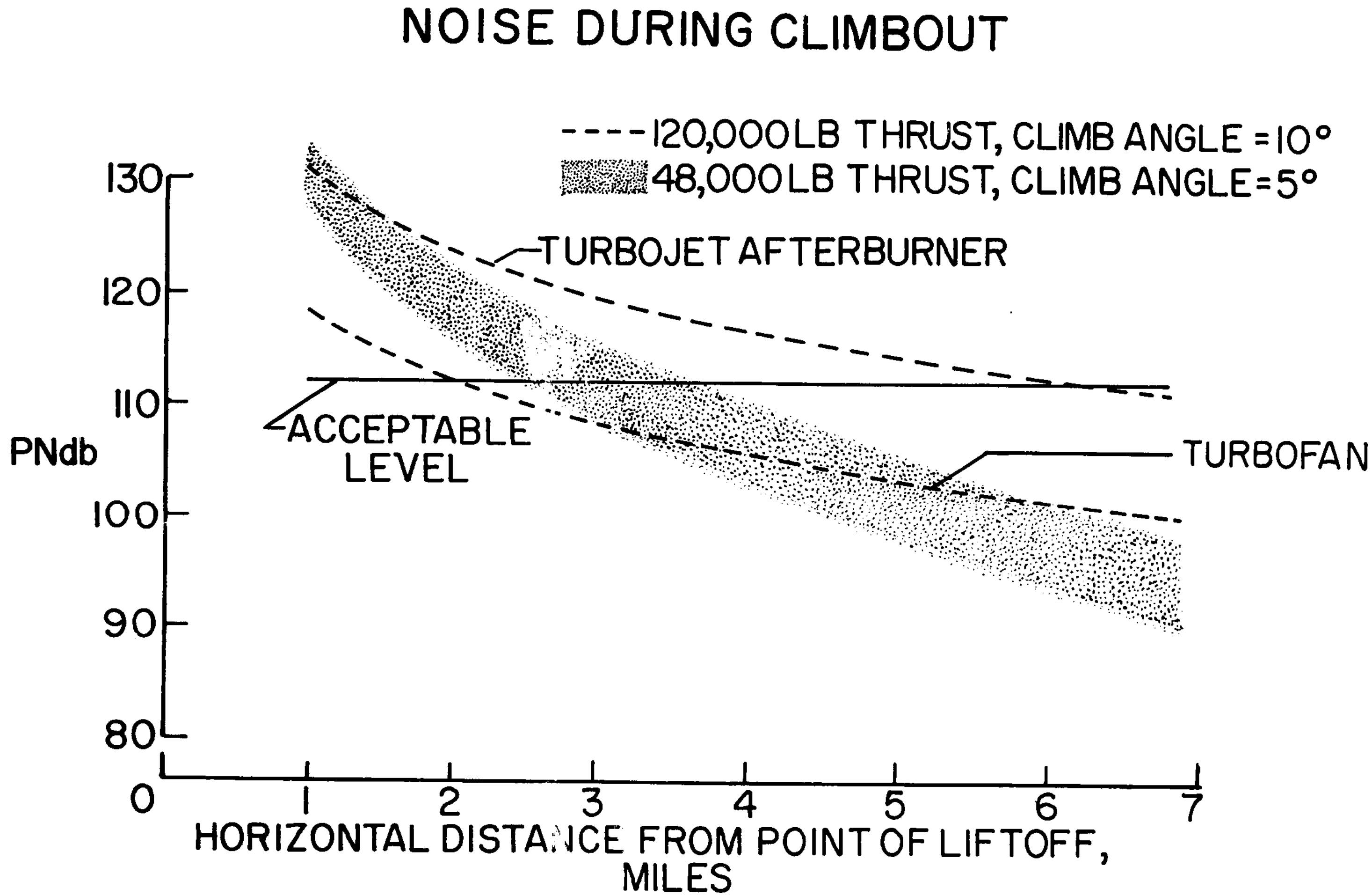
NOISE DURING CLIMBOUT
120,000 LB THRUST, CLIMB ANGLE = 10°
48,000 LB THRUST, CLIMB ANGLE = 5°
TURBOJET AFTERBURNER
ACCEPTABLE LEVEL
TURBOFAN
PNdb
130
120
110
100
90
80
0
1
2
3
4
5
6
7
HORIZONTAL DISTANCE FROM POINT OF LIFTOFF, MILES

Figure 2

BOUNDARY LAYER NOISE DURING CRUISE CONDITION

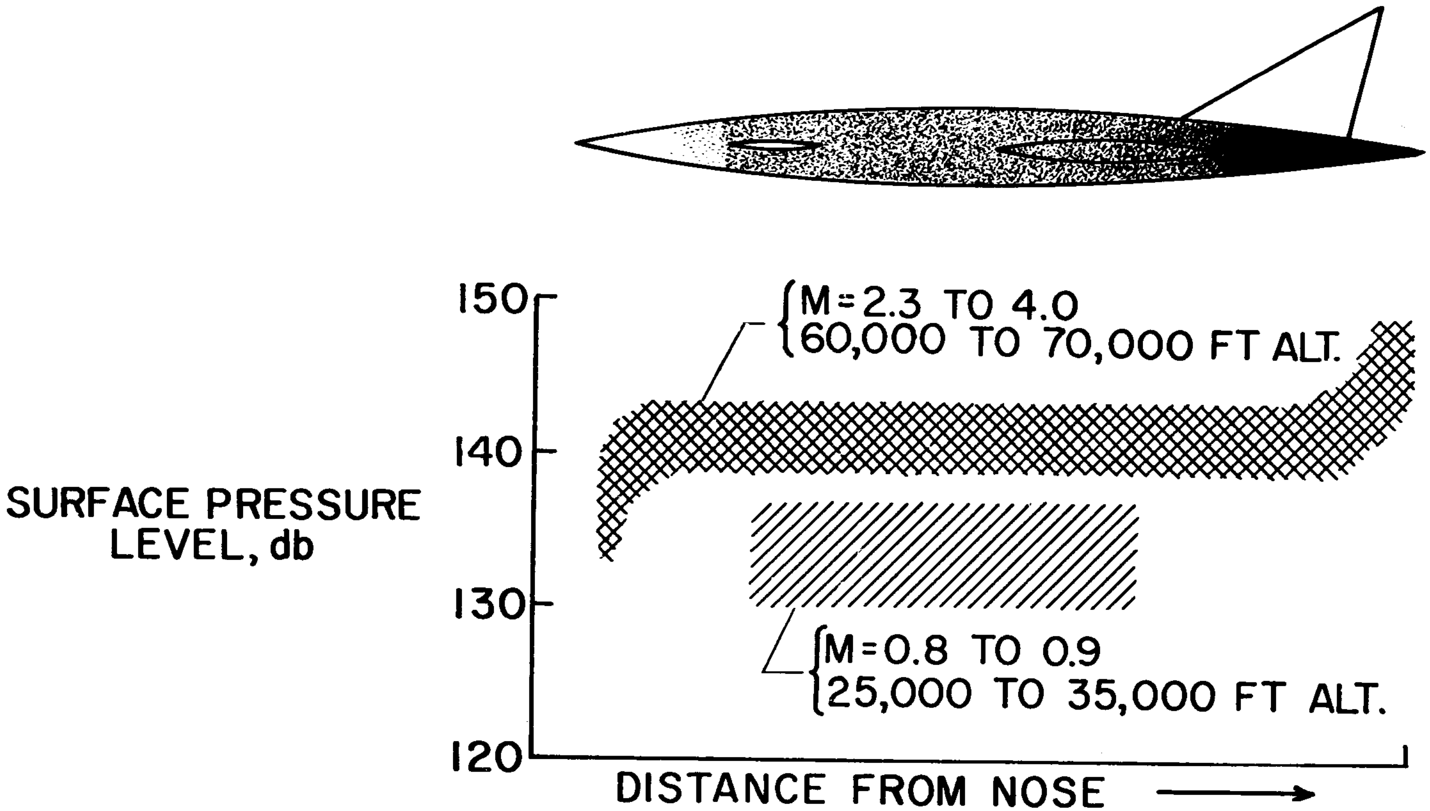

Figure 3

CLIMB SCHEDULES TO AVOID DAMAGE

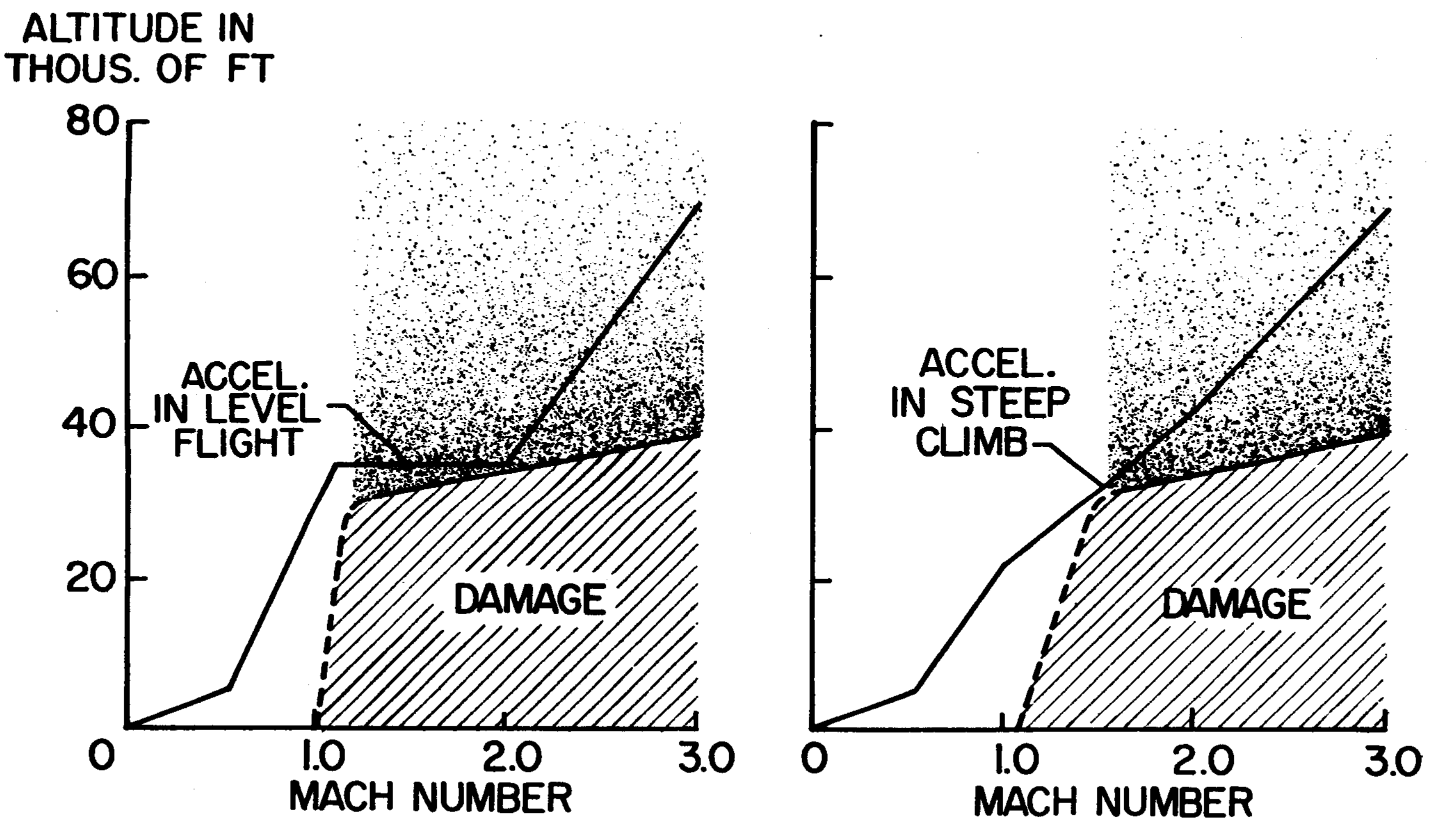

Figure 4

III. STRUCTURES AND MATERIALS PROBLEMS ASSOCIATED WITH SUPERSONIC TRANSPORTS

By Eldon E. Mathauser

Some of the specific structural and materials problems associated with supersonic transports are noted below:

(1) Type of construction

(2) Available materials

(3) General problem areas
  (a) Fatigue
  (b) Creep

(4) Special problem areas
  (a) Air conditioning
  (b) Construction costs

Before these problems are discussed a brief review of the magnitude of the structural temperatures that will be encountered in supersonic flight will be made. Figure 1 indicates the structural temperatures that will be encountered in level flight for different Mach numbers at an altitude of 70,000 feet. Temperatures that will be encountered at a station 1 foot back of the leading edge and 100 feet back of the leading edge are indicated by the upper and lower curves, respectively. Note that at $M = 2$, the structural temperature at the 1-foot station is slightly in excess of 200° F (the boiling point of water), at $M = 3$ the temperature is almost 500° F, and at $M = 4$ the maximum structural temperature exceeds 800° F. The difference in temperatures between the 1-foot and 100-foot stations is approximately 40° F at $M = 2$, 80° F at $M = 3$, and 120° F at $M = 4$. The horizontal tick mark indicates a temperature of 300° F. In past preliminary studies, some temperature between 300° F and 350° F has often been considered to be the maximum operating temperature for aluminum-alloy structures, corresponding to a Mach number range of 2.3 to 2.5. Above this temperature range other materials such as titanium alloy or stainless steel would be required for the aircraft structure. However, as will be noted later, a temperature approaching 350° F for aluminum alloys is tolerable only if the total time at temperature is short.

Various types of construction have been investigated for possible application to the structure of the supersonic transport. In this paper two types will be considered to see how structural weight varies with temperature. In figure 2 the variation of weight with temperature is shown for the familiar skin-stringer type of construction. The materials considered are aluminum alloy, titanium alloy, and stainless steel. (See refs. 1, 2, and 3.) All weights are shown relative to the weight of aluminum-alloy construction at room temperature. The curves are applicable to low values of structural index representative of the values associated with the supersonic transport. The lowest curve, shown by the dashed line, is applicable to beryllium and is shown for comparison purposes only. (See ref. 4.) The vertical dashed line is included to indicate the temperature associated with $M = 3$.

The curves shown in figure 2 are calculated on the assumption that the structure fails by buckling. They indicate that aluminum permits a lighter structure than titanium or stainless steel until the temperature is quite high. However, this conclusion must be modified heavily in practice, as will be shown subsequently.

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Figure 3 shows similar weight curves for sandwich-type structures, again relative to an aluminum structure at room temperature. It should be noted that the best sandwich structure at room temperature (which defines unit weight in fig. 3) does not have the same weight as the best skin-stringer structure; consequently, the curves of figures 2 and 3 are not directly comparable. Only the increase in weight for higher operating temperatures can be deduced from the figures. For the conditions assumed for figure 3, it is evident that aluminum alloy gives structures several times heavier than titanium or stainless steel at speeds well below $M = 3$. Even at room temperature, the aluminum-alloy structure is somewhat heavier than the others.

Relative to figure 2, the following observation should be made. In a complete transport structure, approximately half of the material may tend to fail in tension rather than by buckling. For this part of the material, the curves of figure 3 are more nearly applicable than those of figure 2. Thus, in a complete skin-stringer structure, aluminum is not so efficient structurally as is suggested by figure 2.

Figures 2 and 3 show that only a moderate weight penalty is incurred by a change from room temperature to 800° F, regardless of type of construction (skin-stringer or sandwich), for either titanium or stainless steel. For aluminum, on the other hand, large weight penalties may be incurred. More detailed studies indicate that these penalties would be incurred at speeds well below $M = 3$ except in special cases.

The lowest curve in both figures, shown by the dashed line, is applicable to beryllium. It is of interest to note that for both types of construction considered, beryllium structures indicated the least weight over the entire temperature range considered. It should be mentioned that even though beryllium structures possess an apparent weight advantage over structures fabricated from other materials, widespread use of this material may not occur because of several factors. One of these factors is scarcity. Scarcity coupled with high fabrication costs may limit its use in many structural applications. Another factor, toxicity, is of concern. Toxicity would require special precautions with respect to maintenance and structural repairs. Toxicity may also be a problem for a beryllium aircraft in the event of a crash followed by fire.

The curves shown in figures 2 and 3 are applicable to experimental airplanes, for which only a short life is required, or to supersonic-dash types which spend only a small fraction of their lives at the design temperature. For commercial transports, however, a life of 30,000 hours is generally considered as a minimum goal, and most of this life will be spent at the design temperature. Figure 4 shows that the strength of aluminum alloy deteriorates steadily with long-time exposure to temperature. The curve shows that after 30,000 hours at 350° F (M = 2.5) the strength has dropped to approximately 53 percent of the room-temperature value. Stainless steel and titanium alloy suffer no deterioration due to exposure under these conditions, so far as is known, and can readily give twice as high a structural efficiency.

A few comparisons will now be made between the two types of construction that have been discussed. It can be shown, in general, that sandwich construction leads to lower structural weight than skin-stringer construction for low values of structural or loading index. (See ref. 5 and 6.) In certain cases sandwich construction can lead to structural weights that are 50 to 75 percent of the weight of skin-stringer construction. Even though sandwich construction generally possesses a significant weight advantage over skin-stringer construction, the use of sandwiches may be limited for several reasons. First, the cost of sandwich construction is considerably higher than that of the skin-stringer type. Additional details regarding construction costs will be discussed later. Furthermore, because of limited usage to date, it is not known whether sandwich construction possesses the reliability and serviceability that exists with skin-stringer construction, and the full theoretical gain cannot be achieved in practice because of difficulties of joining pieces. The selection of the particular type of construction is expected to be made not only on the basis of structural weight but also on the basis of cost, reliability, ease of inspection and maintenance, surface smoothness, fatigue life, and various other factors.

A few comments will now be made about the remaining problem areas. These problems are as follows:

(1) Fatigue
- (a) Materials and structures
- (b) Sonic (noise) fatigue
- (c) Explosive failure

(2) Creep

(3) Air conditioning

(4) Construction costs
  (a) Skin-stringer ($25 per lb)
  (b) Sandwich plate ($200 per lb)

Fatigue is perhaps the most important structural problem associated with present-day aircraft. (See ref. 7.) Increasing aircraft speeds into the supersonic range is expected to compound the complexity of the fatigue problem (including sonic fatigue) because an additional parameter, temperature, is introduced. Comparatively little information is available on the fatigue behavior of materials at elevated temperature and practically no information is available on fatigue of aircraft structural components. Research into this field will undoubtedly accelerate when the environmental conditions and types of construction are more clearly defined. One problem associated with fatigue that will continue to be of concern is the problem of explosive failure of pressurized fuselages. Research into this problem at room temperature has been underway for several years. Very few studies of this type have been made to extend the knowledge to the temperatures associated with the supersonic transport.

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Creep, in general, is not expected to be a problem of major concern in supersonic transports for titanium-alloy or stainless-steel construction. NASA studies have shown that creep will not occur at the working stresses to which the structures will be subjected at elevated temperatures. The exception to this may occur if aluminum-alloy structures are used at temperatures above 300° F for long periods. (See ref. 8.)

Air conditioning will be of special concern in flight at supersonic speeds. Special attention to insulation and air conditioning of spaces for the passengers, crew, and cargo will be required, and at the high Mach numbers heat-protection systems for the fuel may be necessary. If conventional insulation and air-conditioning systems are employed to maintain cabin temperature at, say, 70° F, sufficient weight may be involved to effectively increase fuselage weight as much as 50 percent. New concepts in maintaining satisfactory temperatures within the aircraft are being considered and these indicate that efficient and relatively lightweight cooling systems may be obtained.

One of the major items of concern regarding the supersonic transport is construction cost. Two types of construction have been discussed here. Of these, the skin-stringer type is considerably cheaper than the sandwich-plate construction. Skin-stringer construction utilizing conventional aluminum alloys costs approximately $25 per pound of structure.

For sandwich construction utilizing brazed honeycomb this cost may approach $200 per pound of structure. Because of such large differences in construction costs, many studies will be needed to determine the type of construction to be used. The high cost of sandwich construction coupled with the substantial saving in structural weight will be compared with cheaper methods of construction that result in increased structural weights. At the present time it cannot be said which type of construction will be favored. The predicted overall economy of the aircraft will obviously be a major factor in the selection of the type of construction.

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STRUCTURAL TEMPERATURES FOR SUPERSONIC TRANSPORTS
ALTITUDE 70,000 FT

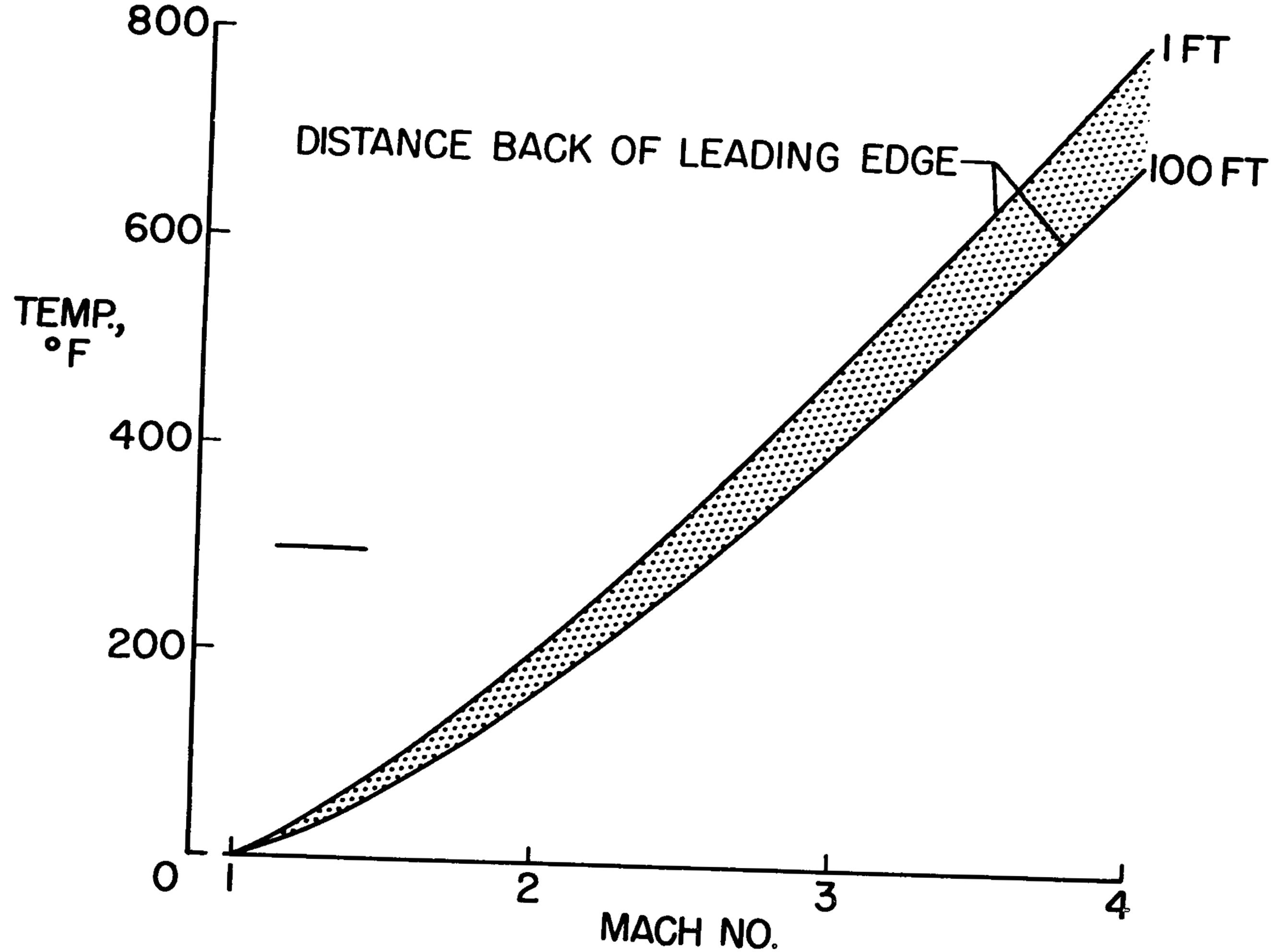

Figure 1

A

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STRUCTURAL WEIGHT, SKIN-STRINGER CONSTRUCTION

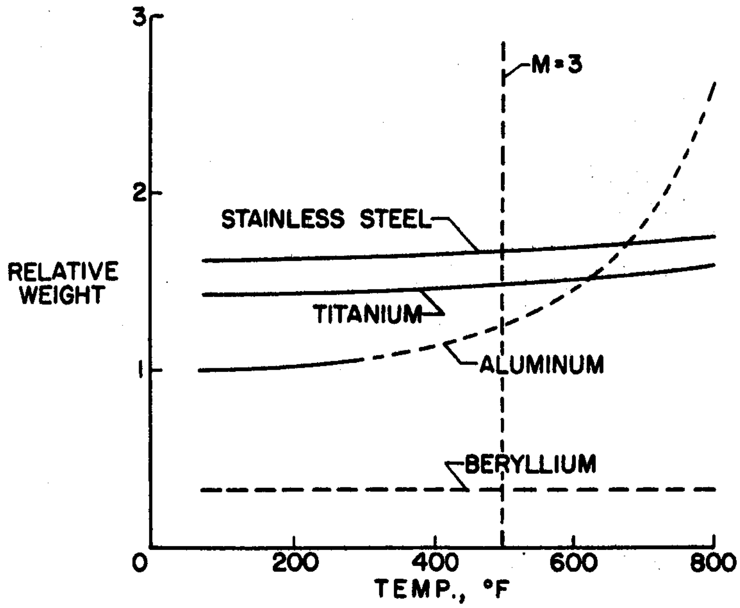


Figure 2

STRUCTURAL WEIGHT, SANDWICH CONSTRUCTION

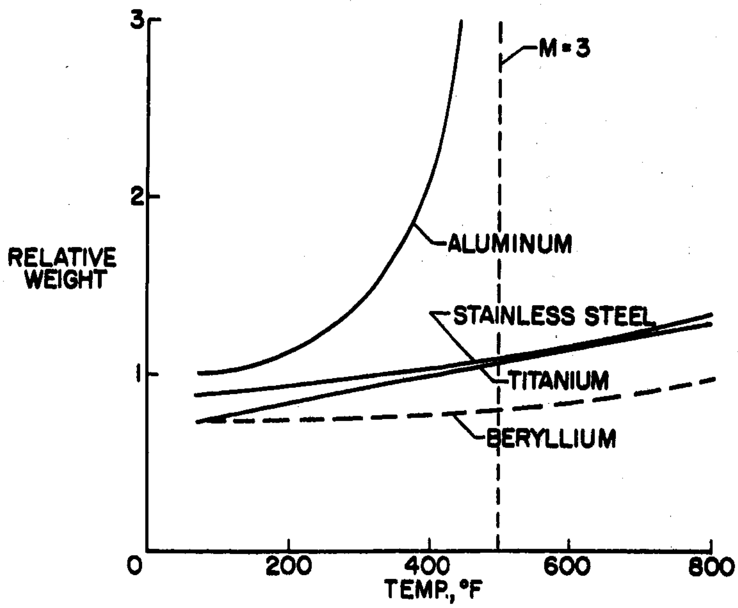


Figure 3

STRENGTH DETERIORATION OF 2024 ALUMINUM ALLOY DUE TO EXPOSURE AT 350° F

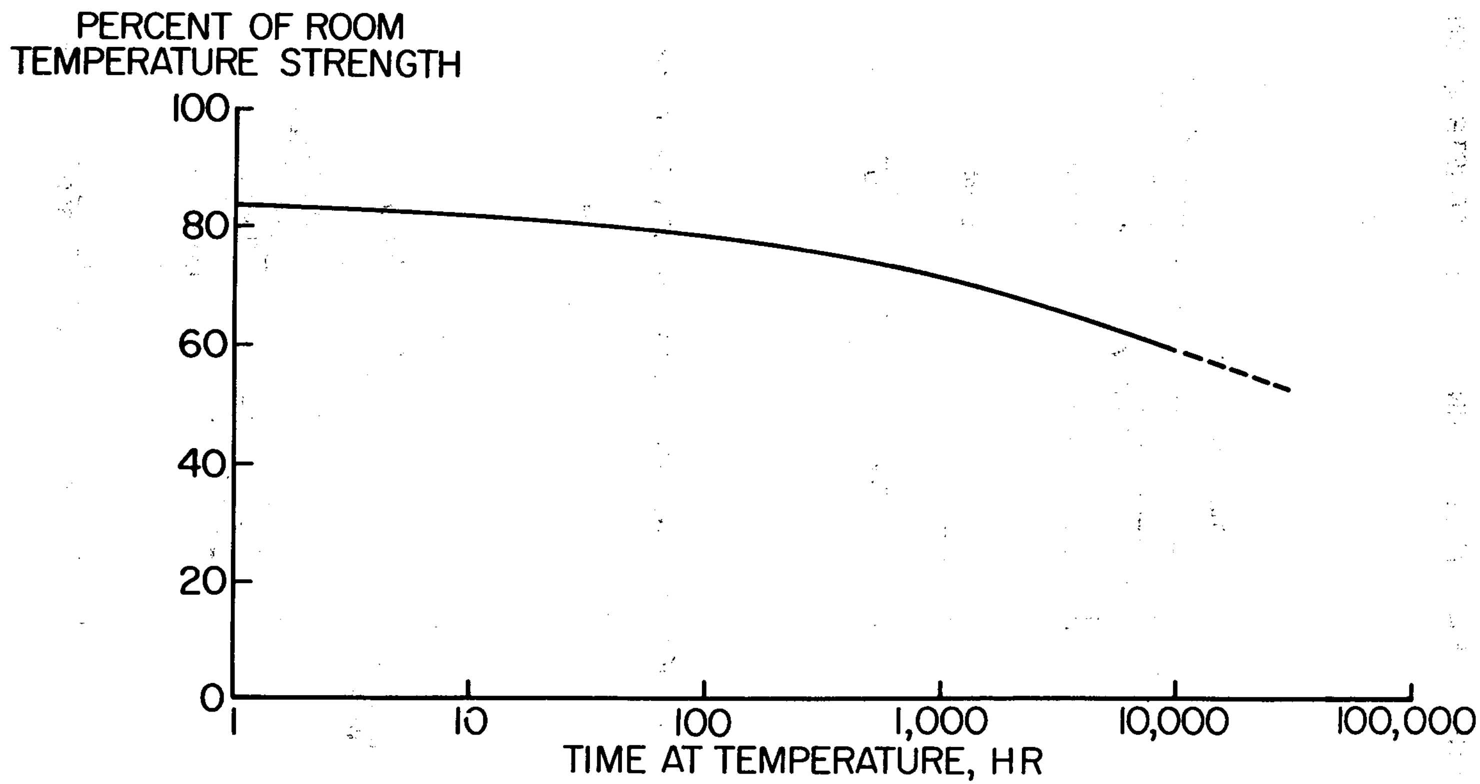


Figure 4

IV. STRUCTURAL LOADS ON SUPERSONIC TRANSPORTS

By Thomas L. Coleman

The structural design of supersonic transports will require consideration of loading conditions which are somewhat more severe than those associated with present transports. As an illustration, figure 1 shows some of the major differences between the design conditions for the two types of transports. The altitude, Mach number, and dynamic pressures for which the supersonic jet must be designed will be two to three times the design values for current transports. Design weight may be twice that of current airplanes. The advent of the hot structure, of either aluminum or steel, will constitute a new loads design area for transports. In addition, the change in configuration from the subsonic flexible-winged vehicles having distributed wing weight in the form of fuel and engines to the slender vehicles having most of the weight concentrated along the fuselage will have a major bearing on the loads design.

The ultimate and fatigue strength which must be provided in order to insure the structural integrity of the supersonic transport under the conditions shown in figure 1 will depend, of course, upon the loads which are likely to be experienced during the lifetime of the airplane. At present, there are a number of problems which need study in order that these loadings can be reliably estimated. Some of the areas which require consideration are as follows:

(1) Gusts

(2) Maneuvers

(3) Ground loads

(4) Flutter and buffet

(5) Pressurization

(6) Design and operating speeds

Relative to the gust loads, the major problems concern (1) the turbulent environment at high altitude, (2) airplane slowdown and turbulence avoidance capabilities, and (3) airplane response characteristics to rough air. At present, only limited data are available on the amount and intensity of rough air at high altitude. Additional research will be required, therefore, in order to define better the gust environment for the supersonic jet. Of particular interest is the turbulence associated with the jet stream and the mountain-wave phenomenon.

Initial studies indicate that at low altitudes and subsonic speeds the supersonic jet will have slowdown capabilities comparable to subsonic jets. However, operation at reduced speed while traversing extensive areas of turbulence will increase fuel consumption to such an extent that the slowdown procedure may not be operationally feasible. At cruising speeds, the supersonic transport cannot effectively slow down. Although it is felt that this situation may not be too serious because of the apparent infrequency of severe turbulence at high altitude, additional studies of the slowdown concept for supersonic airplanes will be required to clarify the situation.

The gust response characteristics of configurations for supersonic jets may be quite different from the characteristics of present transports as regards both vertical and horizontal gusts. Questions here concern both the rigid body and flexible response modes and, in particular, the flexible responses of the fuselage. In order to determine how these response characteristics will affect the gust loads, flight tests of supersonic airplanes, analytical studies, and, possibly, wind-tunnel tests will be required.

The maneuver loads imposed on the airplane during routine operational flights and during pilot and airplane check flights will undoubtedly continue to be a major part of the total loads experienced. The operational maneuvers will depend to some extent on the manner in which the transport is integrated into the air traffic system. Likewise, more extensive use of flight simulators and greater reliance on ground checkout of the airplane could influence the number of maneuvers experienced during pilot and airplane check flights. From the overall viewpoint, however, it does not appear that maneuver loads for the supersonic transport will be different from present experience with subsonic jets.

Relative to ground loads, there are indications that the supersonic transport will attain higher speeds on the runway and may have higher sinking speeds than current jets. It may be expected that the airplane loads which will accompany these higher speeds will be somewhat more severe than those experienced by current transports.

Flutter and buffeting will remain as problems to be considered in design and will require close attention so as not to limit unduly the speed and maneuvering capabilities of the supersonic jet. Increased pressurization loads will result from the higher operating altitude and will magnify the problem of insuring the structural integrity of the cabin.

The selection of structural design speeds for the rough-air, cruise, and dive conditions and the definition of operational speeds, such as the normal operating and never-exceed speeds, will become more complicated because of the increased speed ranges and the increased emphasis placed on optimum speeds. In this regard, it appears that the current concept of defining design and operational speeds will have to be reexamined in the light of the supersonic jet slowdown capabilities, the effect of off-optimum speeds on performance, and the speed limitations imposed by the engines.

Although there are many unknowns in loads study, some preliminary estimates of the flight and ground loads have been made to obtain an indication of the general level of loadings which may be expected. Figure 2 shows a comparison of the estimated gust accelerations for supersonic and subsonic jets. The ordinate scale is the average number of accelerations per mile of flight and the abscissa scale gives the gust acceleration increment. The canard configuration and flight profile shown in part I by Mark R. Nichols were used together with the conventional gust equation to estimate the accelerations for the supersonic jet. Based on this simple analysis, it appears that the gust accelerations for the two types of jets will be about equal. Another point of interest is that, to the extent that the accelerations can be taken as a measure of riding comfort, the two transports are comparable.

The determination of fatigue life for the supersonic transport will be even more difficult than it is for present transports due in part to complications associated with elevated structural temperatures. As a first approach to examining the fatigue problem, however, crude estimates of the relative fatigue damage that will be caused by maneuvers, gusts, and ground loads have been made and are shown in figure 3. In making these estimates the effects of elevated temperature on the fatigue life were ignored. On this basis, about 40 percent of the total fatigue damage is ascribed to maneuvers, 50 percent to gusts, and 10 percent to ground loads. This distribution of fatigue damage is comparable to that which has been estimated for a subsonic jet, except for the increase indicated for ground loads.

The effect of elevated temperatures on the estimates in figure 3 is not known. It will depend to some extent, however, upon the percentage of total loads which occur while the structure is hot. At present, it is estimated that less than 25 to 30 percent of the gust and maneuver loads will occur at high temperature. This estimate suggests that the overall fatigue life may not be significantly affected by the elevated temperatures. Additional research will be required, however, to reach a conclusion.

In summary, the structural loads design of the supersonic transport will encompass loading conditions which are more severe than those for current transports. A number of load problem areas exist which will require additional study in order to insure the structural integrity of the supersonic transport as regards both ultimate and fatigue strength. Prominent among these problems are (1) the effects of elevated temperature on fatigue life, (2) the response characteristics of the new configurations to rough air, and (3) the definition of structural design speeds.

DESIGN CONDITIONS

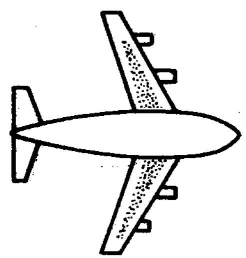
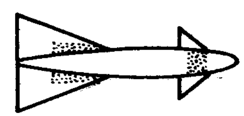
	SUBSONIC JET	SUPERSONIC JET
ALTITUDE, FT	40,000	75,000
M	.95	2 TO 3
DYN. PRESS.	600	1400
WEIGHT, LB	300,000	400,000 TO 600,000
TEMP.	COLD	500° F
MATERIAL	ALUMINUM	ALUM. OR STEEL
CONFIGURATION		

Figure 1

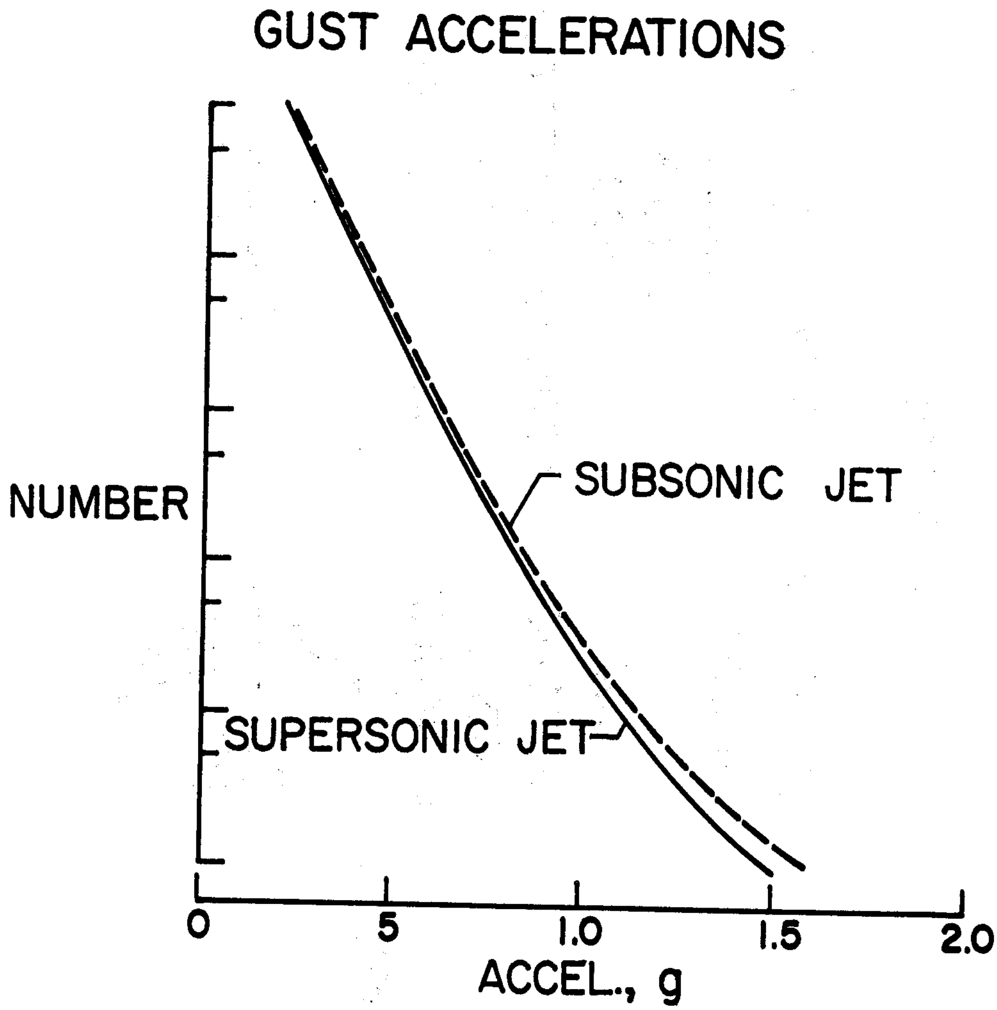

GUST ACCELERATIONS
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Figure 2

FATIGUE

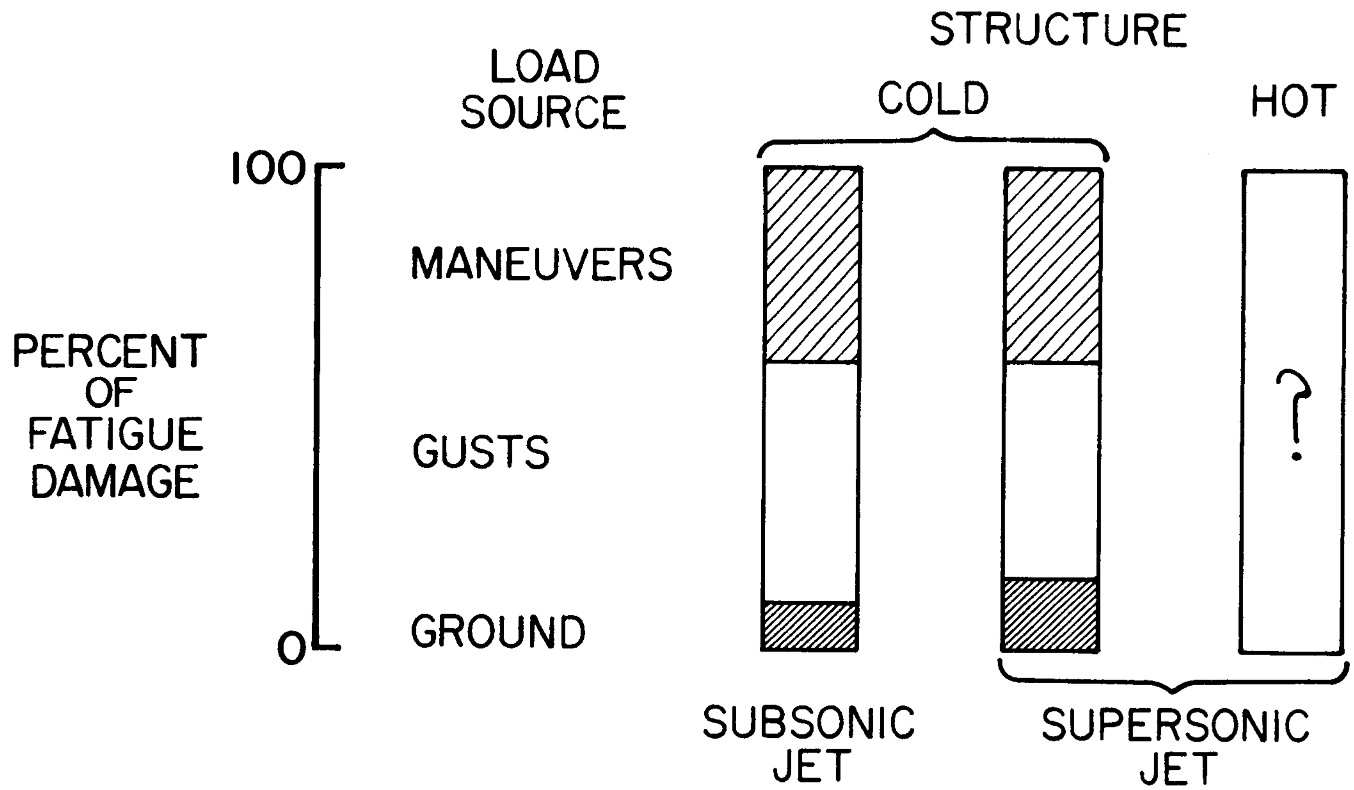

Figure 3

V. FLYING QUALITIES OF SUPERSONIC TRANSPORTS

By Ralph W. Stone, Jr.

In view of the available information on the requirements for satisfactory flying qualities of current aircraft (see refs. 1 to 3) a review of these requirements is not necessary at this time. However, inasmuch as man is relatively unchanging in this age of revolutionary technological changes, his opinions concerning satisfactory flying qualities and aircraft characteristics significant to satisfactory flying qualities will be the same (or nearly so) for supersonic transports as they are for current aircraft. Thus, only certain significant differences between prospective supersonic transports and current transports and the effect of these differences on the flying qualities of the supersonic aircraft are discussed herein. The stability of an aircraft is a very basic element of its flying qualities and, for brevity, the comments herein will be confined to this aspect of flying qualities.

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Because of the complex nature of airplane stability, the following symbols will be useful to an understanding of the results:

b	span, ft
$\bar{c}$	mean aerodynamic chord, ft
$C_{1/2}$	number of cycles for oscillation to damp to one-half amplitude
C_L	lift coefficient, $\frac{\text{Lift force}}{qS}$
C_l	rolling-moment coefficient, $\frac{\text{Rolling moment}}{qSb}$
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment}}{qS\bar{c}}$
C_n	yawing-moment coefficient, $\frac{\text{Yawing moment}}{qSb}$
C_Y	side-force coefficient, $\frac{\text{Side force}}{qS}$
g	acceleration of gravity, 32.17 ft/sec^2

I_X moment of inertia about X principal body axis, slug-ft^2

I_Y moment of inertia about Y principal body axis, slug-ft^2

I_Z moment of inertia about Z principal body axis, slug-ft^2

M Mach number

p,q,r angular velocities of airplane about X-, Y-, and Z-axes, radians/sec

q dynamic pressure, $\frac{1}{2}\rho V^2$, lb/sq ft

S wing area, sq ft

v lateral velocity, ft/sec

V speed, ft/sec

α angle of attack

β sideslip angle

ρ air density, slugs/cu ft

ϕ roll angle

Derivatives:

$$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha}$$

$$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$$

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$$

$$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a}$$

$$C_{l_{\delta_r}} = \frac{\partial C_l}{\partial \delta_r}$$

$$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$$

$$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}}$$

$$C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}}$$

$$C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$$

$$C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$$

The results presented in this paper are for hypothetical aircraft for which the dimensional, mass, and inertia characteristics and operating conditions are shown in table I. The aerodynamic data used (tables II and III) are from wind-tunnel tests and computations for configurations similar to current reciprocating-engine transports, current jet transports, and, of course, prospective supersonic transports. Actual current aircraft probably have stability characteristics that are somewhat different than shown, but for the comparative purpose of this paper the model and computed data are considered adequate.

The longitudinal dynamic stability (ref. 4) shown herein is based on two-degree-of-freedom calculations of the short-period motions. The long-period or phugoid motions are not considered in this paper. The lateral dynamic stability (refs. 5 and 6) shown herein is based on the three degrees of lateral-directional freedom. Only data for the Dutch roll oscillation are shown. The spiral and rolling modes are not presented, although future more-detailed studies must consider these factors

Inertia coupling (refs. 7 and 8) between the longitudinal and lateral modes of motion and aerodynamic coupling, including that of control deflection, are also not included although they may be significant in any final design of both the airplane and the damping systems. Nonlinearities in aerodynamic characteristics such as might occur in low-speed flight at large angles of attack are not included but may have significant influence on the aircraft flying qualities.

The first element of stability is the aerodynamic stability of the aircraft. In figure 1 are shown the pitching moment due to angle of attack C_{m_α} and the yawing moment due to sideslip angle C_{n_β} as functions of Mach number. These results are typical for configurations that have been considered as possible supersonic transports. A very drastic variation of these stability derivatives through the Mach number range is noted. The variations shown here are in a large part the result of lift-curve-slope reductions with increasing supersonic speed, which are common to all aerodynamic surfaces. All stability derivatives generally will be affected in a similar manner. Clearly then any fixed-geometry supersonic aircraft will experience large variations in aerodynamic stability throughout the speed range. Another point to be noted in figure 1 is the appreciable reduction of C_{n_β}, at a cruising Mach number of 3, below its value existing subsonically.

The aerodynamic stability characteristics are, however, only a part of the stability picture. The flight conditions, particularly the high altitudes to be used, and the distribution of the weight in the airplane are factors which combine with the aerodynamic stability derivatives to make the dynamic stability of the airplane.

In figure 2 are shown the differences in weight distribution in the prospective jet transports as compared with current jets and reciprocating-engine transports. Shown are relative values for the prospective supersonic transports and current jet transports compared with values for current reciprocating-engine transports.

Because of the necessity for slenderness in construction for supersonic aircraft, the weight of the supersonic transport will be distributed much differently than that of current transports. The moment of inertia I_X (the distribution of weight along the wings) may be less, the moment of inertia I_Y (the distribution of weight along the fuselage) will be much greater, and I_Z will be also considerably larger than for current transports. Relative changes of this nature have a tendency to cause deterioration of the lateral dynamic stability, and the greater magnitudes of the moments of inertia cause motions and responses to be more sluggish.

The last factor shown in figure 2, the relative density (an effective ratio of the airplane's density to the density of the air in which it is flying), is most significant to dynamic stability. The larger it is, the less stable is the airplane. As this factor is a density ratio, the altitude directly affects it. The differences shown are for cruising flight where the supersonic transport flys at altitudes 2 to 3 times higher than do existing transports. At comparable altitudes, as in landing-approach conditions, the relative density will be only about 1 to $1\frac{1}{2}$ times larger for the supersonic transport than for current transports.

The effects of these various differences on the dynamic longitudinal stability characteristics for current aircraft and the prospective jet transports are shown in figure 3. Here is plotted the damping of the short-period longitudinal motion (in terms of the reciprocal of cycles to damp to 1/2 amplitude) as a function of the period of the motion. Moving upward on the chart leads to more satisfactory stability. The chart is divided into areas of unsatisfactory, acceptable, and satisfactory regions. The regions shown are based on current military specifications (ref. 9) which are in reasonable accord with NASA information and opinions.

Shown for comparison are points representing current reciprocating transports (the squares), current jets (the triangles), and a hypothetical supersonic transport (the circles). Open symbols are for cruising flight and the solid symbols are for low-altitude, low-speed flight. Current reciprocating-engine transports are satisfactory for all realms of flight. Current jets are less well damped and appear only acceptable and not satisfactory in cruising flight. The supersonic transport is lower still in the chart in cruising flight, approaching the unsatisfactory region, so that a potential, if not almost certain, need for automatic pitch damping is indicated. Although for low-altitude, low-speed flight the supersonic transport may lie in the satisfactory region, the period is so large (13 seconds) that it may be of considerable annoyance and may require special alertness in flight.

The dynamic lateral stability also presents challenging problems, as is shown in figure 4. Here again is plotted damping where, as in figure 3, moving up the chart indicates more satisfactory stability. The abscissa is the ratio of the bank angle ϕ to the lateral velocity v, increasing values of which are less desirable.

Shown are boundaries which divide the chart into areas of intolerable, tolerable, and satisfactory characteristics. Tolerable means primarily a condition which would be accepted only in emergencies, as when automatic damping fails. The regions shown are based on current military specifications which are in reasonable accord with NASA information and opinions.

Shown in figure 4 are data for current reciprocating-engine transports (the square symbols) that are satisfactory in cruising and in low-speed, low-altitude flight and for current jets (the triangular symbols) that are barely satisfactory in cruising flight although somewhat better in low-speed flight.

Because of the extreme dependence of lateral stability on the specific configuration, two sets of points are shown in figure 4 for the prospective supersonic jet transports. These represent roughly practical extremes of characteristics which are possible for these aircraft. (See tables I to III.) The stability in cruising flight will not be acceptable without automatic damping. The flagged symbols in figure 4 represent conditions with automatic damping and show that satisfactory conditions can be obtained. For the condition on the right, however, an excessive amount of automatic damping is required to attain satisfactory stability. In low-altitude, low-speed flight, conditions are somewhat better for the supersonic transport but automatic damping still appears to be a requisite for satisfactory flying qualities. As no fixed-geometry supersonic aircraft can have compatible aerodynamic stability characteristics throughout its speed range, no aircraft can have compatible dynamic stability characteristics throughout its range of operating conditions (including altitude) unless automatic damping and/or control is used.

In summary, no fixed-geometry supersonic transport can have compatible aerodynamic stability characteristics throughout its speed range. Furthermore, the flying qualities, through their intimate dependence on dynamic stability, will vary greatly throughout the flight envelope. Automatic damping about all three axes will probably be required for supersonic jet transports.

During future development programs, investigations must be made of the aerodynamic stability and of methods to improve it that are compatible with performance requirements. Studies of simple and reliable automatic damping systems of course must also be performed.

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TABLE I.- DIMENSIONAL, MASS, AND INERTIA

CHARACTERISTICS AND FLIGHT CONDITIONS

	Current reciprocating engine	Current jet	Supersonic jet	
Weight, lb	128,000	270,000	400,000	
I_X, slug-ft^2	1,500,000	3,050,000	2,520,000	1,000,000
I_Y, slug-ft^2	880,000	2,995,000	6,000,000	10,000,000
I_Z, slug-ft^2	2,300,000	6,000,000	8,360,000	10,750,000
W/S, lb/sq ft . . .	80	96	92	
S, sq ft	1,600	2,800	4,300	
b, ft	120	140	90	
Maximum cruising altitude, ft . . .	20,000	35,000	75,000	
Air density, ρ, slugs/cu ft . . .	0.001267	0.000737	0.000109	
Cruising speed, ft/sec	510	900	3,390	

TABLE II.- AERODYNAMIC STABILITY CHARACTERISTICS - CRUISING FLIGHT

Derivative	Current reciprocating engine	Current jet	Supersonic jet	
C_{L_α}	0.15	0.063	0.024	
C_{m_α}	-0.024	-0.029	-0.0015	
C_{m_q}	-30	-16	-4.8	
C_{Y_β}	-0.016	-0.025	-0.0087	-0.0087
C_{l_β}	-0.001	-0.0035	-0.00175	-0.0010
C_{n_β}	0.002	0.004	0.0014	0.0010
C_{l_p}	-0.55	-0.49	-0.16	-0.11
C_{n_p}	0.015	0.045	0.031	0.008
C_{n_r}	-0.340	-0.286	-0.200	-0.12
C_{l_r}	0.051	0.075	0.006	0.014

TABLE III.- AERODYNAMIC STABILITY CHARACTERISTICS - LOW-ALTITUDE, LOW-SPEED FLIGHT

Derivative	Current reciprocating engine	Current jet	Supersonic jet	
C_{L_α}	0.15	0.063	0.040	
C_{m_α}	0.0246	0.0266	0.0025	
C_{m_q}	-30	-16	-48	
C_{Y_β}	-0.016	-0.023	-0.0117	-0.0117
C_{l_β}	-0.001	-0.0033	-0.00232	-0.0014
C_{n_β}	0.002	0.0037	0.00192	0.0014
C_{l_p}	-0.55	-0.455	-0.213	-0.146
C_{n_p}	0.015	0.042	0.0413	0.011
C_{n_r}	-0.340	-0.267	-0.266	-0.16
C_{l_r}	0.051	0.070	0.008	0.0186

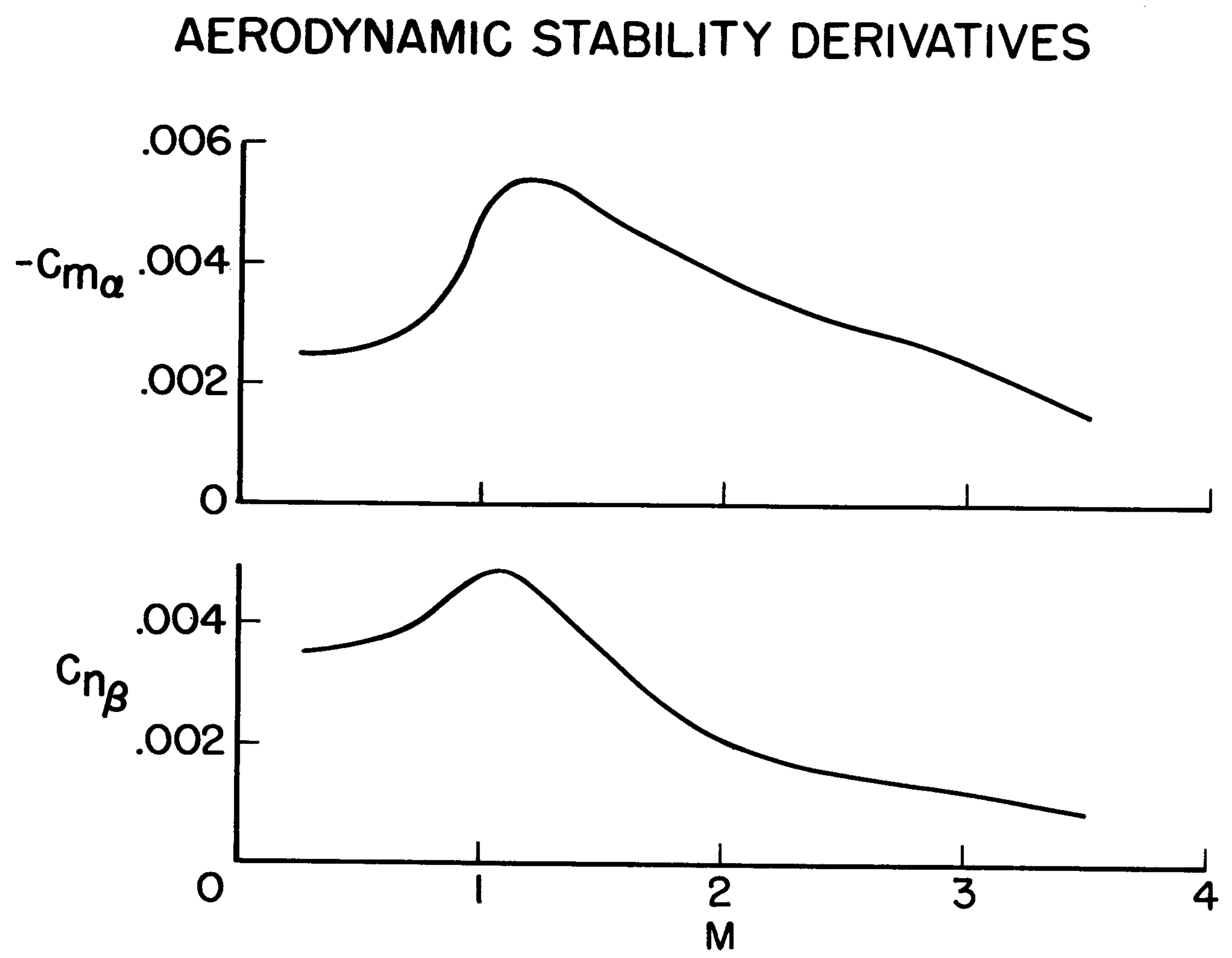

AERODYNAMIC STABILITY DERIVATIVES
$-C_{m_\alpha}$
.006
.004
.002
0
C_{n_β}
.004
.002
0
1
2
3
4
M

Figure 1

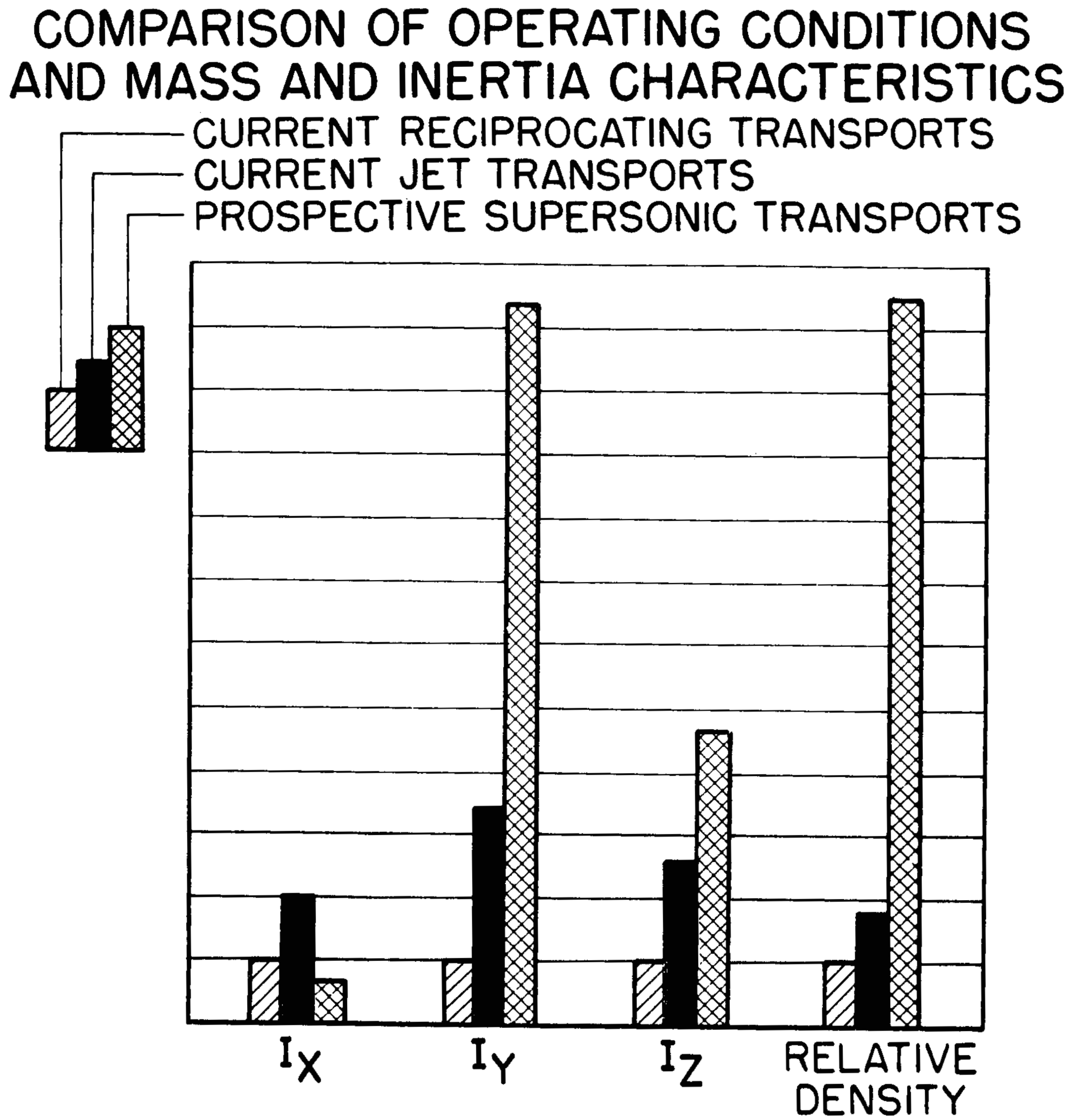

COMPARISON OF OPERATING CONDITIONS
AND MASS AND INERTIA CHARACTERISTICS
CURRENT RECIPROCATING TRANSPORTS
CURRENT JET TRANSPORTS
PROSPECTIVE SUPERSONIC TRANSPORTS
I_X
I_Y
I_Z
RELATIVE DENSITY

Figure 2

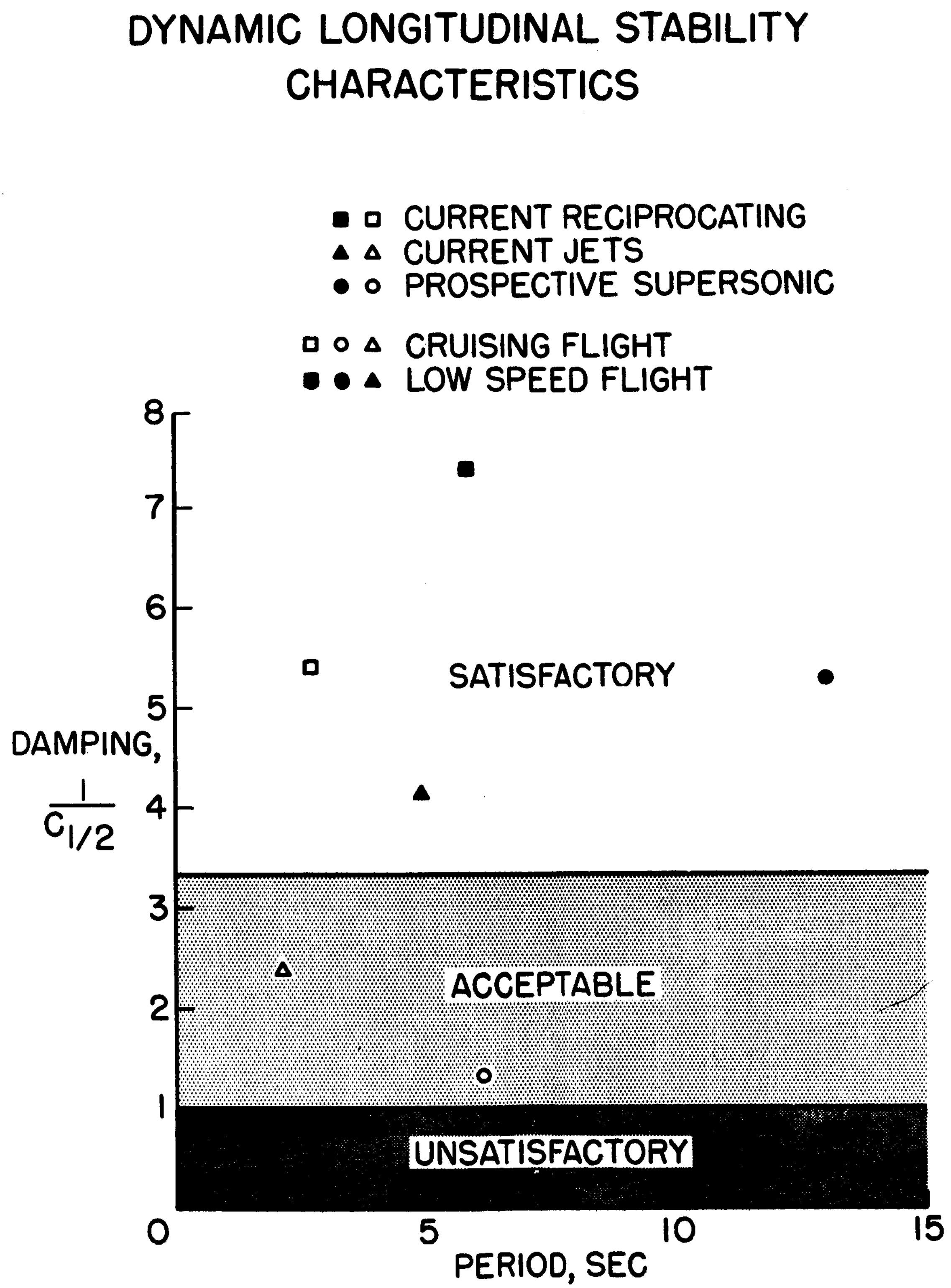

DYNAMIC LONGITUDINAL STABILITY CHARACTERISTICS
CURRENT RECIPROCATING
CURRENT JETS
PROSPECTIVE SUPERSONIC
CRUISING FLIGHT
LOW SPEED FLIGHT
8
7
6
5
4
3
2
1
0
DAMPING, $\frac{1}{C_{1/2}}$
SATISFACTORY
ACCEPTABLE
UNSATISFACTORY
5
10
15
PERIOD, SEC

Figure 3

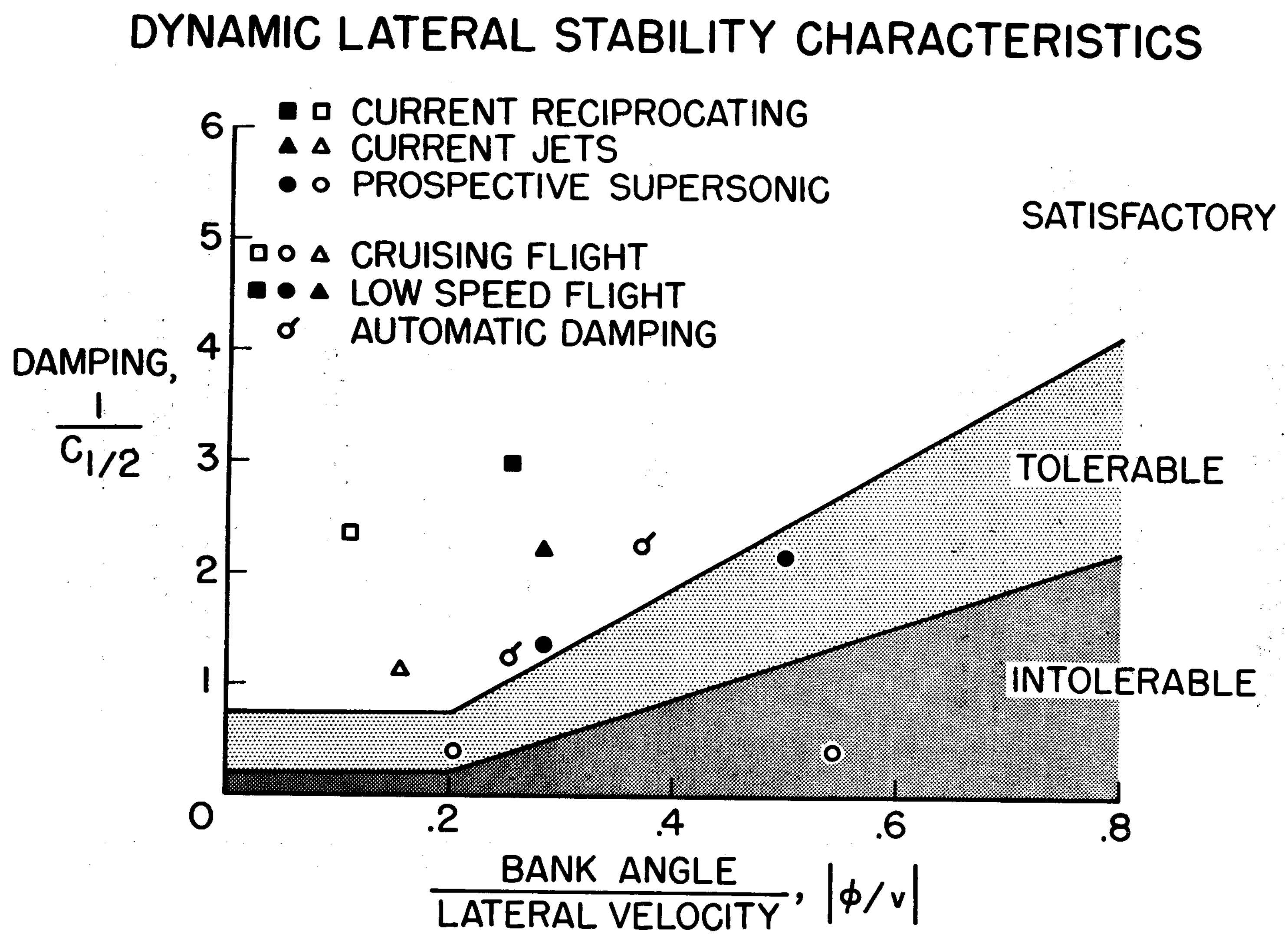

DYNAMIC LATERAL STABILITY CHARACTERISTICS
CURRENT RECIPROCATING
CURRENT JETS
PROSPECTIVE SUPERSONIC
CRUISING FLIGHT
LOW SPEED FLIGHT
AUTOMATIC DAMPING
SATISFACTORY
TOLERABLE
INTOLERABLE
DAMPING, $\frac{1}{C_{1/2}}$
0
1
2
3
4
5
6
.2
.4
.6
.8
$\frac{\text{BANK ANGLE}}{\text{LATERAL VELOCITY}}, |\phi/v|$

Figure 4

VI. RUNWAY AND BRAKING REQUIREMENTS

By Joseph W. Wetmore

One of the important factors to be considered for a supersonic transport airplane is the runway requirement. An indication of the runway lengths required for supersonic transports, as presently envisaged, and a comparison with the requirements for the present jet transports are given in figure 1. Runway length is plotted against take-off speed. Curves are shown for different thrust-weight ratios. The solid-line curves represent a family of supersonic transports, of the canard-delta type, assumed to be powered by six engines, and the dashed-line curves are for a family of four-engine subsonic jet transports. Values of runway length are based on current Civil Air Regulations (CAR SR422B) for turbine transports in which the balanced field concept is used and hot-day, no-wind conditions are assumed. The shaded area in the right-hand part of the figure indicates the probable operating region of supersonic transports in terms of speed and thrust-weight ratio or acceleration. The area in the left-hand part of the figure indicates the approximate operating conditions of the subsonic jets. Note that take-off speeds for the supersonic transports are expected to be appreciably higher than take-off speeds for the subsonic transports because of the poorer lift development capability of the supersonic wing configuration. A usable lift coefficient of 0.75 is assumed for take-off and landing. As indicated in figure 1, the take-off speeds for supersonic transports will be in the range of 175 to 190 knots as compared with 135 to 150 knots for the subsonic jet transports. The effect of the relatively high take-off speed of the supersonic transport on the runway length requirement is largely offset, however, by higher acceleration in the take-off, resulting from the greater thrust-weight ratio inherent in a supersonic transport. Studies indicate that the thrust-weight ratio for a supersonic transport must be at least 0.3; whereas, present jet transports operate with thrust-weight ratios of 0.2 or less. The net result is that runway lengths required for a supersonic transport will tend to be somewhat longer - possibly 1,000 to 1,500 feet - than for the present jet transports, for equivalent mission capabilities.

Runway length requirements for landing are indicated in figure 2. The landing runway length, again determined in accordance with current Civil Air Regulations, is plotted against landing speed. The same curve applies to both the supersonic and subsonic jet transports with the assumption that braking capabilities are the same for both. Here, as in the take-off, the landing speed is expected to be somewhat higher for the supersonic than for the subsonic airplane because of the inferior lift characteristics of the supersonic configuration. However, the speed difference is not as large as for take-off, because, with a greater proportion of its take-off weight in fuel, the supersonic transport should be more lightly loaded at landing than its subsonic counterpart. As indicated in figure 2, the higher landing speed will result in a moderate increase in landing runway length for supersonic transports of the canard-delta type over that for the subsonic jets of about the same magnitude as for the take-off.

Apart from runway length, other requirements must be considered for runways and taxiways expected to accommodate supersonic transports. One of these requirements is adequate load-bearing capability. The supersonic transport is expected to have a gross weight variously estimated to be from 30 to 100 percent more than the subsonic jet transports; thus, present runways may have to be strengthened. Another factor that will need consideration is the degree of runway roughness that can be tolerated. An answer to this question will require studies of the response of supersonic transport configurations to runway roughness.

The higher take-off and landing speeds indicated in figures 1 and 2 for the supersonic transport may have important implications in the problem of decelerating the airplane in aborted take-off and landing, which is already a critical problem with the present jet transports. For the take-off abort, it is estimated that about 30 percent more kinetic energy per pound of aircraft weight must be dissipated in braking from the critical speed for the supersonic transport than for the subsonic jets. In the less severe but more frequent landing case, the energy dissipation required is about 15 percent greater for the supersonic airplane. In order to meet these severe energy absorption requirements, it will probably be necessary to develop improved wheel brakes, possibly with some form of auxiliary cooling, or resort to other braking devices, such as parachutes, skids, or emergency arresting gears. Work will continue toward improving the low-speed lift characteristics of the supersonic transport configurations through such devices as variable geometry, improved flaps, and so forth. Even a moderate increase in lift capability can have a substantial effect in reducing take-off and landing runway requirements and in alleviating the braking problem.

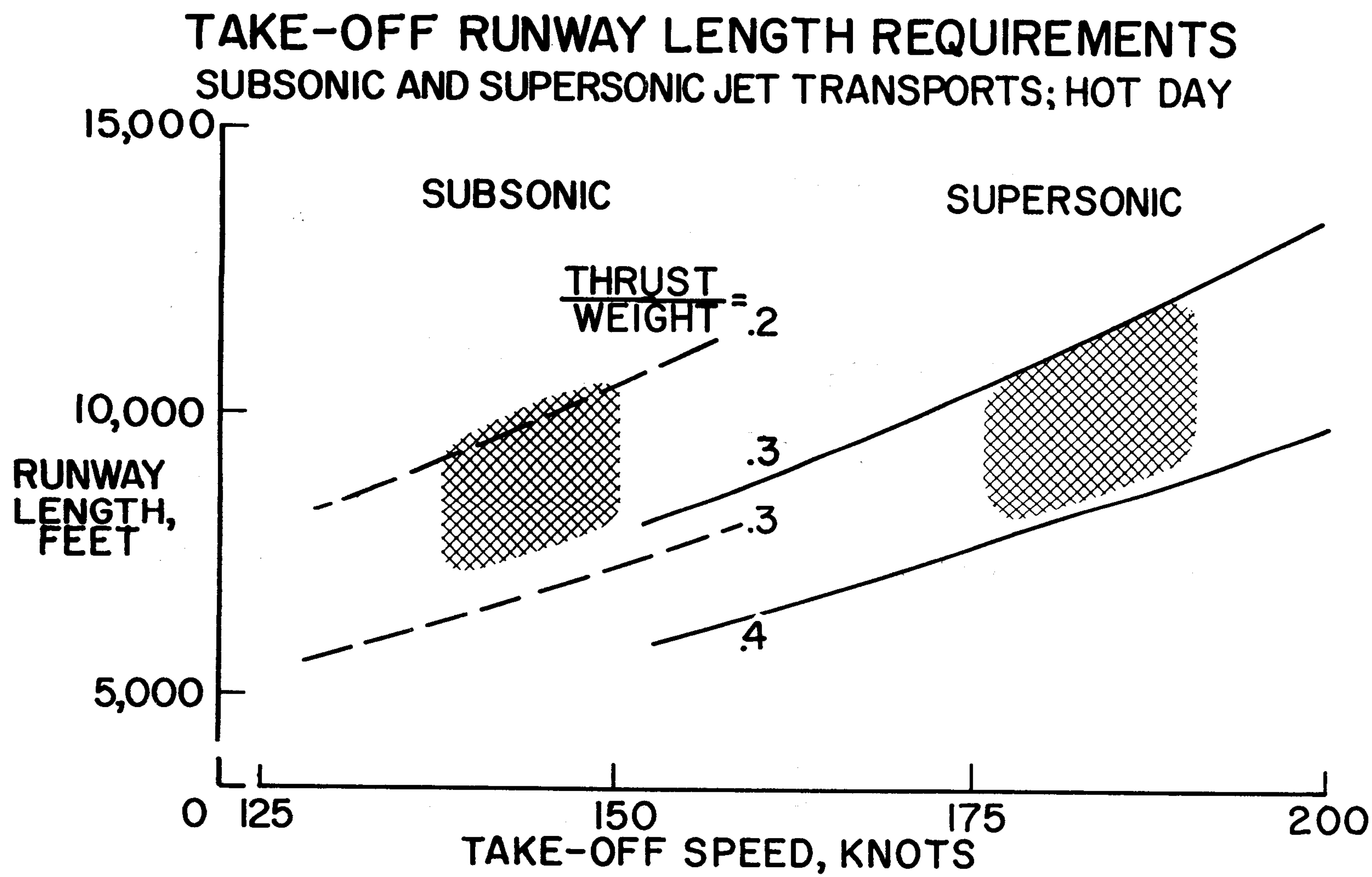

TAKE-OFF RUNWAY LENGTH REQUIREMENTS
SUBSONIC AND SUPERSONIC JET TRANSPORTS; HOT DAY
15,000
10,000
5,000
RUNWAY LENGTH, FEET
SUBSONIC
SUPERSONIC
THRUST/WEIGHT = .2
.3
.3
.4
0
125
150
175
200
TAKE-OFF SPEED, KNOTS

Figure 1

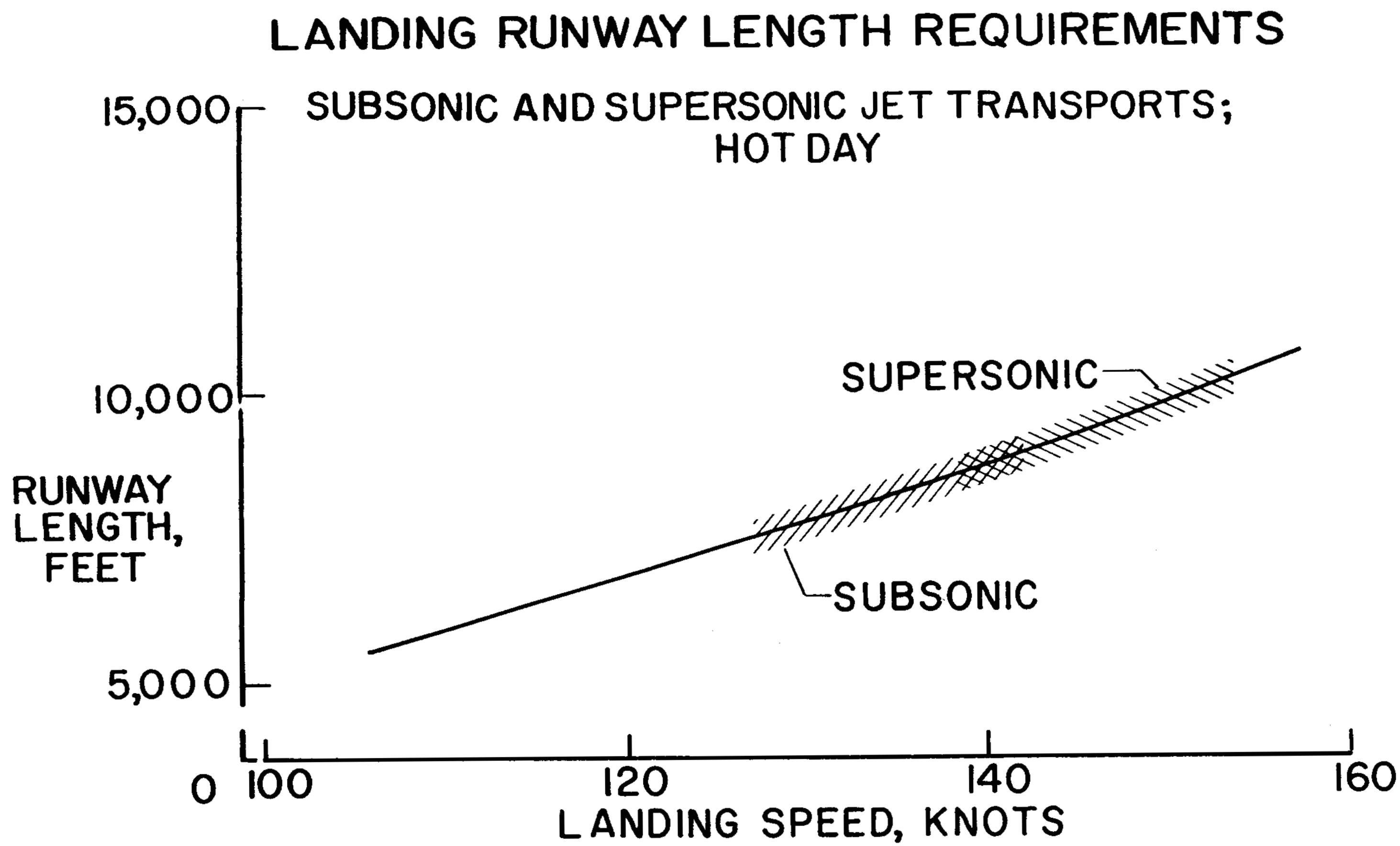

LANDING RUNWAY LENGTH REQUIREMENTS
SUBSONIC AND SUPERSONIC JET TRANSPORTS;
HOT DAY
15,000
10,000
5,000
RUNWAY
LENGTH,
FEET
SUPERSONIC
SUBSONIC
0
100
120
140
160
LANDING SPEED, KNOTS

Figure 2

VII. AIRWAY TRAFFIC CONTROL AND OPERATIONS

By James B. Whitten

A typical flight profile for a supersonic transport is illustrated in figure 1. The initial climb and the transition to supersonic flight take place below the altitude level of 40,000 to 45,000 feet where current and future subsonic aircraft will be operating and cover a ground distance of 250 miles. During this climbing portion of the flight, positive separation will be required either by positive control of all traffic in the climb corridor or by collision warning equipment carried by the aircraft. Devious flight paths or changes in the speed, altitude, and distance profile will not be acceptable for fuel economy reasons. This positive separation by traffic control will be required in visual as well as in instrument flight conditions since flight speeds and requirements for very precise control of the flight path will make visual separation impossible. The cruising portion of the flight path is a cruise climb at a constant Mach number of 3, in which positive separation by traffic control will again be required with a possible backup of airborne collision warning equipment (ref. 1). Figure 2 shows the possibility of providing altitude separation by pressure altimetry. The dashed line shows current regulations for minimum altitude separation against altitude, requiring 1,000-foot separation below 29,000 feet and 2,000-foot separation above 29,000 feet. The solid line labeled "present" shows the separation provided by current pressure altimeters. As can be seen there is presently a small altitude range in which positive separation is not provided in 3 out of 1,000 cases. The two lines labeled "near future" and "future" depict the separation which can be provided with improved instrumentation incorporating null servo-type altimeters and improved air-data computer systems. This shows that a vertical separation of 1,000 feet will be sufficient to the highest altitudes expected for cruise. (Calculation of the penalties involved shows that for constant-altitude cruise compared with an optimum altitude cruise, a maximum additional take-off fuel weight of about 1 percent of take-off gross weight is required.) With this 1,000-foot separation, 8 traffic lanes would be available on each path. On the assumption that most passengers desire both to depart and to arrive between 0800 and 2400 local time and that the normal 15-minute separation is provided, 21 round trips per day could be made along each lane or a total of 168 daily round trips.

Figure 3 shows the initial distance at which a maneuver must be initiated during cruise to provide a 1-mile lateral separation between aircraft on a head-on collision course. Two curves are shown: one for present subsonic jet aircraft, the other for the Mach number 3 transport. It can be seen that even for the highest turn rates possible, the supersonic aircraft must use some means of detection other than visual. The 30° bank angle line is shown for reference. The load factor of 2.5 occurs at a bank angle of about 70°. Maneuvering for collision avoidance may be costly at the higher altitudes since very little excess thrust is available for acceleration after the slowdown caused by the excess drag in maneuvers.

The approach sequence is initiated 400 to 600 miles from the destination before the decelerating portion of the flight is started. If the aircraft must proceed to an alternate, this must be confirmed prior to the slowdown. Accurate navigational information must be provided during the slowdown and descent to allow precise letdown altitude and speed control. Most efficient flight paths to a straight-in approach and landing with no delay must be provided to reduce the fuel reserve requirements to an acceptable minimum. Most studies to date have reduced reserve fuel requirement considerably below those currently allowed by regulatory authorities. Projected improvements in traffic control systems would indicate that some reduction may be feasible. The reserve requirements will, however, to a much larger extent than ever before, dictate the design of the aircraft.

Studies of fuel requirements for some flight emergencies have also been made. Figure 4 shows the effect of losing one engine at midrange. For the 4-engine aircraft, 41 percent of the reserve fuel is required to proceed to the destination; for the 6-engine aircraft, 24 percent; and for the 8-engine aircraft, 17 percent. If there were a complete and sudden loss of pressurization, immediate descent to an altitude not requiring oxygen is not practicable since 100 percent oxygen would not avoid complete pilot and passenger collapse during the descent. A slower loss of pressure or other emergency requiring a descent would require a midrange alternate since the aircraft could neither return to the departure point nor proceed to the destination.

The fuel required in case of failure of the automatic flight control equipment is not known since it involves both the capability of the pilot in holding the precise flight path, the precision of the information furnished to him, and the effect of off-design operation on the fuel required. Failure of the automatic stabilization equipment, particularly the directional channel, might be catastrophic since this would result in intolerably low directional damping which would make it difficult or impossible for the pilot to control the airplane. Aerodynamically, the airplane will be capable of holding subsonically within the holding patterns now specified at altitudes above 15,000 feet. Below 15,000 feet the holding patterns will probably require slightly more area than is presently provided. Holding will be costly from a fuel standpoint and should be considered as an emergency situation. Holding 30 minutes at $M = 0.8$ at 35,000 feet will require an additional 10 percent fuel or about 20,000 pounds, and at $M = 0.40$ at 5,000 feet an additional 12 percent or 22,000 pounds will be required.

Figure 5 summarizes the fuel situation. It can be seen that about 1/3 of the fuel is used in the climb and accelerating portion of the flight, 1/2 in the cruise, and only 8 percent of the initial fuel or 17,000 pounds remains on landing. Looking now at the fuel flow rate it is seen that take-off fuel flow is over 200,000 lb/hr, climb fuel flow with afterburner increases from about 100,000 lb/hr to over 200,000 lb/hr, and cruise fuel flow averages about 50,000 lb/hr. Thus the reserve provided gives little or no margin for off-design conditions.

In summary, this airplane appears to function very much like a projectile. Once launched it must proceed along a very precisely controlled flight path with little or no delays and with a large degree of dependence on automatic flight control and stabilization systems and rapid automatic traffic control over the entire route. The capability of the pilot to assume manual control with the safety, economy, and schedule reliability required of commercial transportation is highly questionable. Research is in progress to develop aircraft and engine configurations of a less critical nature.

REFERENCE

1. Anon.: Altimetry. Paper 215-58/DO-88, Radio Technical Commission for Aeronautics, Nov. 1, 1958.

NEW YORK-PARIS FLIGHT PLAN

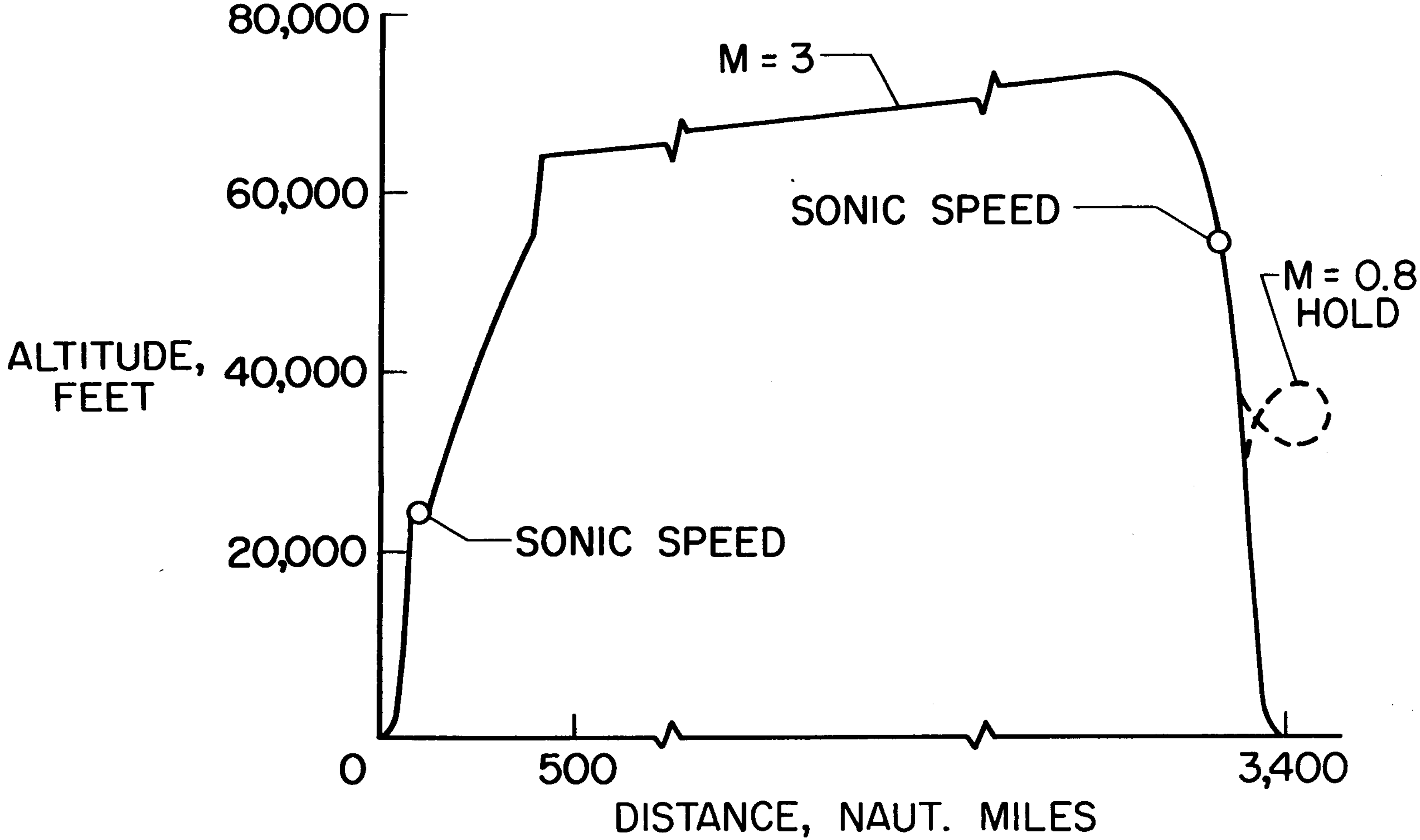


Figure 1

ALTIMETRY ERRORS OF TWO AIRCRAFT
(99.7% PROBABILITY)

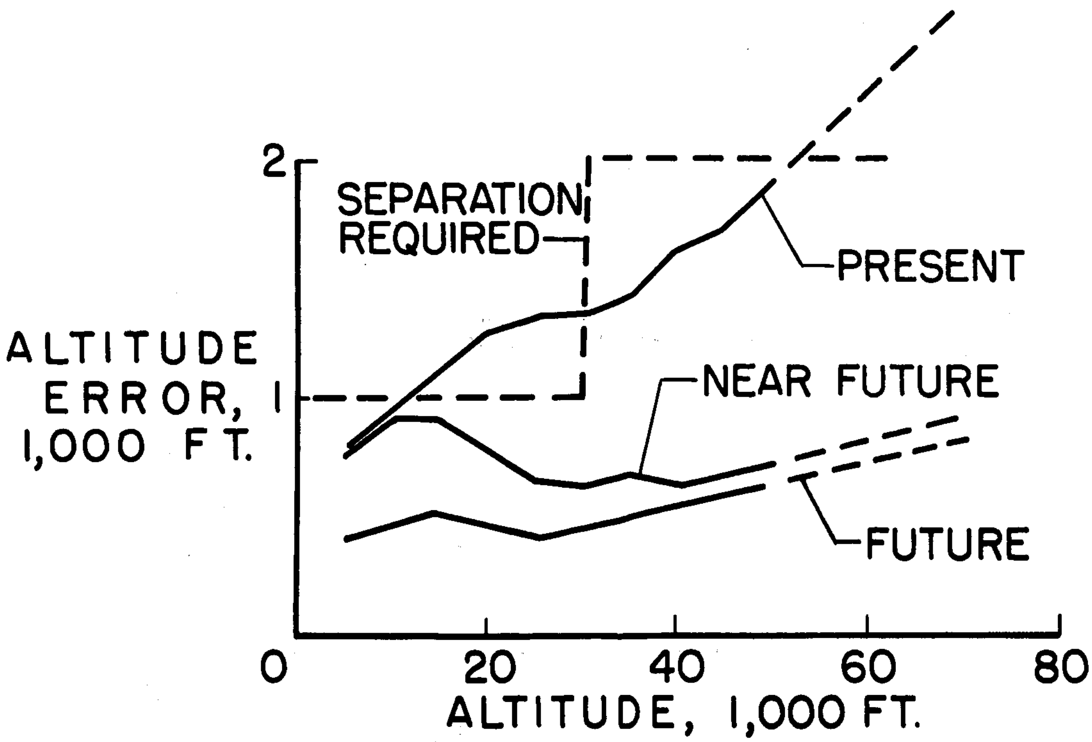


Figure 2

EFFECT OF MACH NUMBER
AND LOAD FACTOR ON COLLISION AVOIDANCE

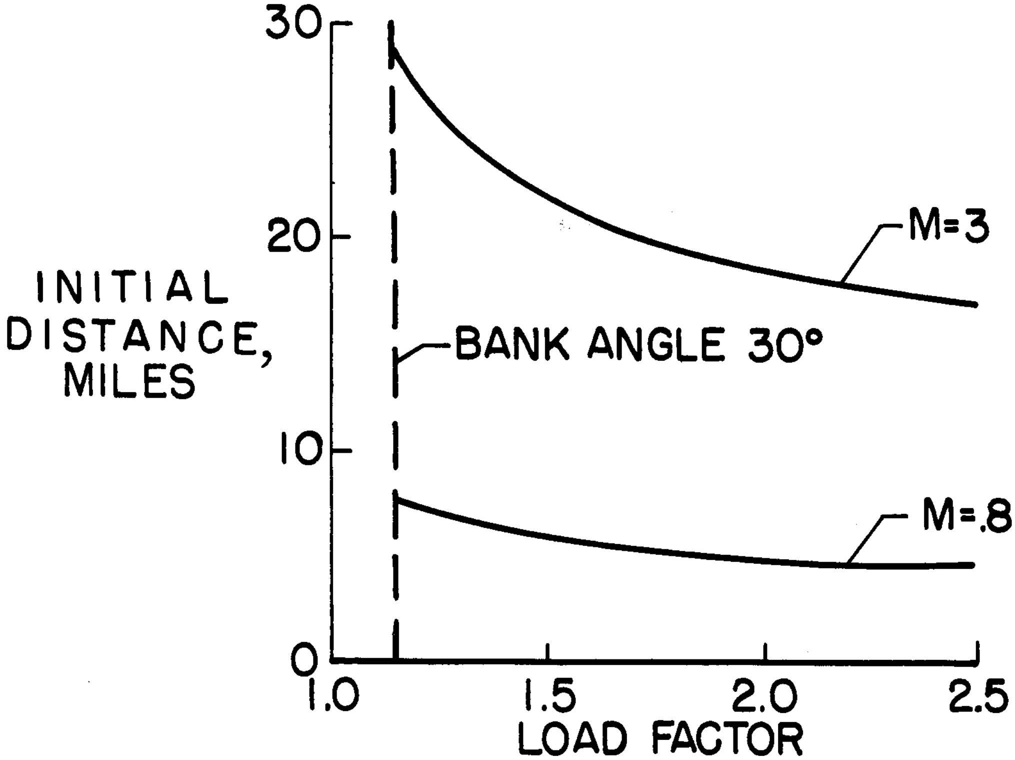


Figure 3

EFFECT OF ENGINE OUT AT HALFWAY ON FUEL CONSUMPTION

NEW YORK TO PARIS

HOT DAY SR 427 FUEL RESERVE

NO. ENGINES	4	6	8
NO. PASSENGERS	51	130	212
WT. AIRPLANE	321,300	482,000	642,000

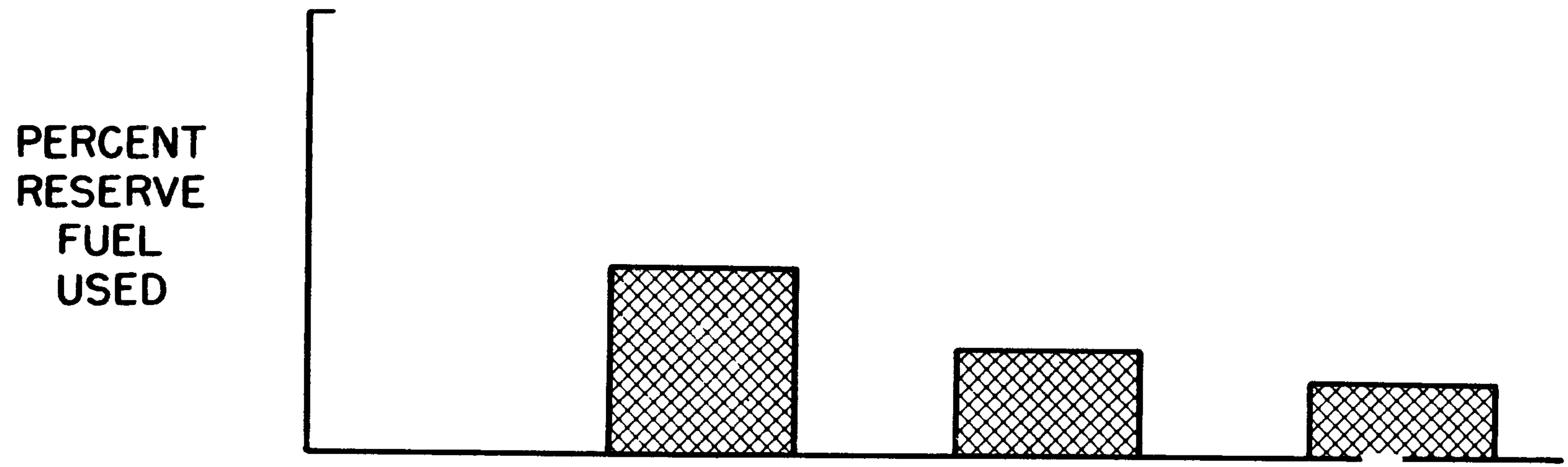


Figure 4

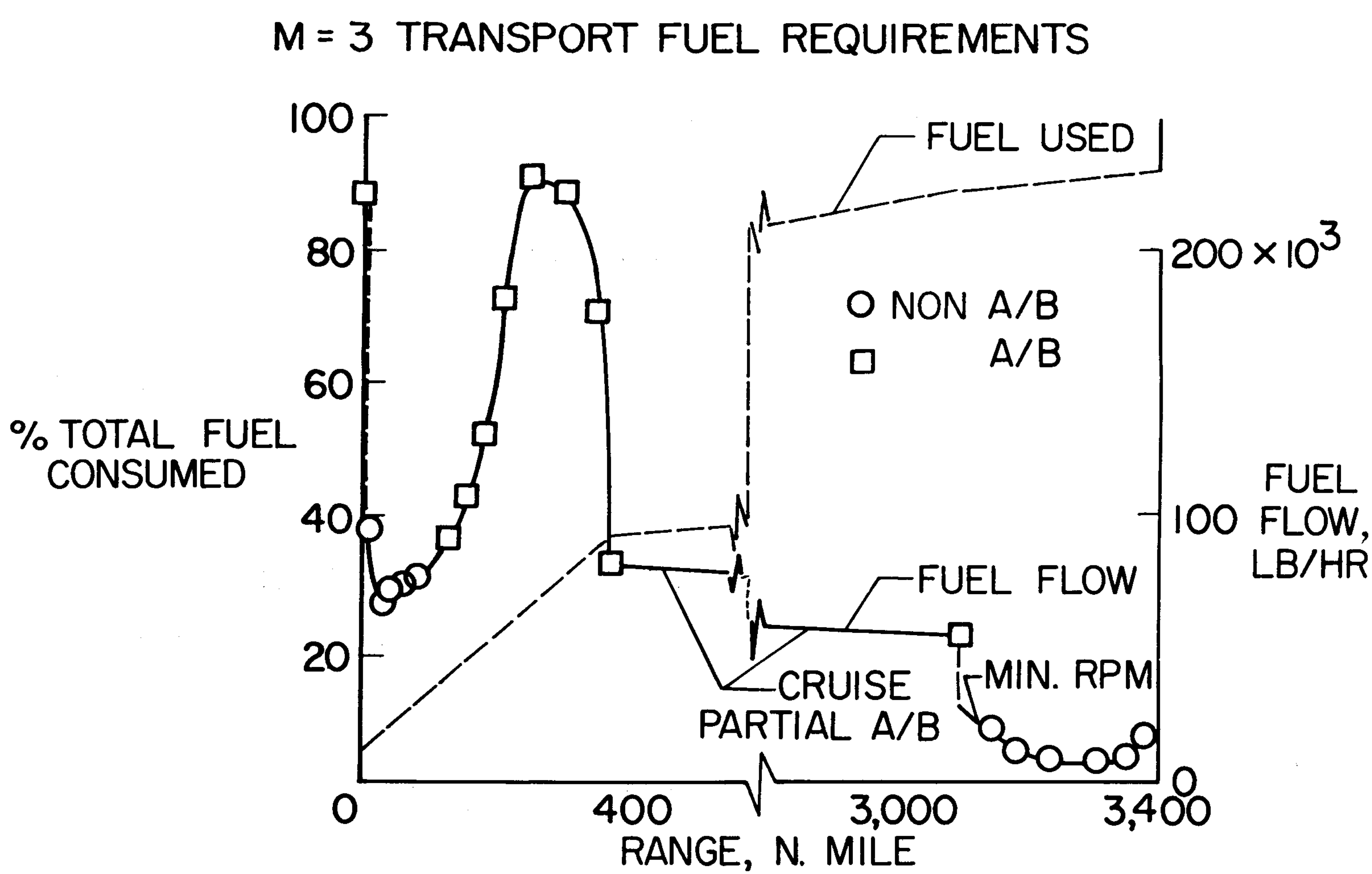

M = 3 TRANSPORT FUEL REQUIREMENTS
% TOTAL FUEL CONSUMED
100
80
60
40
20
0
FUEL USED
200 × 10^3
100
0
FUEL FLOW, LB/HR
NON A/B
A/B
FUEL FLOW
CRUISE PARTIAL A/B
MIN. RPM
400
3,000
3,400
RANGE, N. MILE

Figure 5

VIII. VARIABLE GEOMETRY FOR TRANSPORTS

By Thomas A. Toll

It has been shown that a reasonable range capability probably can be achieved with a supersonic transport. There are, however, certain critical aerodynamic problems with regard to landing and take-off characteristics, the rate of climb at subsonic speeds immediately after take-off, and the ability to cruise or loiter subsonically with reasonable efficiency. These problems result from the fact that the high sweep angles and low aspect ratios needed to achieve the required supersonic performance are not conducive to good low-speed aerodynamics. Two of the problems mentioned, take-off and subsonic climb, can be alleviated by using high ratios of thrust to weight, but this does nothing for the other problems. Alleviation of all of these problems can be accomplished, however, by using some form of variable geometry through which the airplane can be changed in flight from a highly efficient supersonic configuration to at least a reasonably efficient subsonic configuration.

Figure 1 illustrates possible forms of variable geometry applied to the wing. The conventional trailing-edge flap that slides rearward and is deflected down to increase the lift of the wing is a type of variable geometry, and, of course, is the logical arrangement for wings of large span and narrow chord. For the low-aspect-ratio wings typical of supersonic designs, much less can be gained by applying variable geometry to the wing trailing edge, and a more favorable location is at the wing tip. One approach, which has been suggested, involves hinging the wing tip about a longitudinal axis so that the tip is drooped in high-speed flight and is extended horizontally for subsonic operation. Another possibility might involve telescoping a part of the tip in and out of the inboard part of the wing.

The third method, which is potentially the most effective system and has been studied in most detail, involves hinging the wing panels about vertical axes and varying the sweep angle. At one time it was believed that a serious stability problem would be associated with variable sweep because of the longitudinal translation of the center of pressure of the wing panels as their sweep angle is varied. Research programs carried out at the Langley Research Center have shown, however, that it is possible to lay out an airplane configuration that does not experience serious stability changes in spite of the center-of-pressure movement. Extensive studies, both experimental and analytical, have been conducted on applications of variable sweep to military aircraft. These along with our more recent studies on transports have shown that significant improvements in versatility and off-design characteristics can be realized.

Figure 2 shows the situation that exists in the matter of lift for take-off and landing. The solid curves represent a typical subsonic design having wings of high aspect ratio. The dashed curves are representative of low-aspect-ratio supersonic designs. The subsonic airplane has many advantages. First, fairly large amounts of camber and wing incidence can be used so that a substantial increment of lift exists even at zero angle of attack of the airplane. Second, the rate of increase of lift with angle of attack is substantially higher than for the supersonic airplane. Third, because of the large span, trailing-edge flaps are highly effective in that they provide a large increment in lift over the clean configuration. The result is that at practical take-off attitudes of 6° to 10°, essentially the entire lift potential of the wing can be realized.

The clean supersonic airplane will yield reasonably high lift at 25° to 30° angle of attack. This lift is not considered usable, however, for several reasons: first, inclination of the passenger cabin to these angles would be objectionable; second, a landing gear that would allow such inclination would be heavy and cumbersome; and third, the aerodynamic drag would be excessively high. It seems, therefore, that the allowable inclination of the airplane on the ground should be of the order of that used for subsonic aircraft, or at least not greater than about 15°. Thus the problem is to devise means for increasing lift in the lower angle-of-attack range.

As to the use of trailing-edge flaps on supersonic transports, it is possible that a usable lift-coefficient increment of about 0.2 can be realized by the use of conventional high-lift devices consisting of no more than slotted flaps, or perhaps flaps with moderate boundary-layer control. Considerably larger increments probably can be achieved if large amounts of blowing (the jet flap) are accepted. The third dashed curve for the supersonic designs (fig. 2) represents what can quite readily be obtained by a form of span extension such as can be accomplished by variable sweep and with no trailing-edge flaps. If flaps are used in addition to the span extension, the lift can be further increased; however, even without flaps, lift values somewhat higher than those attainable for the basic wing with conventional trailing-edge flaps are attainable in the angle-of-attack range of interest. An additional advantage, not shown here, of the span extension over the flapped wing is that the lift is accomplished with less aerodynamic drag and should, thereby, permit faster acceleration in take-off.

The drag at lift is a primary consideration for problems other than take-off and landing - that is, for subsonic climb and the efficiency of subsonic cruise and loiter. Figure 3 shows that the clean supersonic airplane fares very badly in comparison with the clean subsonic airplane with regard to drag at the higher lift values. The span extension that could be achieved by variable sweep reduces the drag essentially to that of the subsonic airplane over a good part of the lift range. This would be expected to give considerably improved rates of climb as well as reduced fuel consumption for subsonic cruise or for loiter in the landing pattern.

Studies presently are underway on various configurations of supersonic transports using variable geometry. One of these configurations is shown in figures 4 and 5. This arrangement would be expected to yield essentially the aerodynamic improvement shown in the previous figures for the case of span extension. The outer panels of the wings are set at 67° leading-edge sweep for supersonic flight and are rotated forward to 27° for subsonic operation. The accompanying aspect-ratio variation is from 1.9 to 4.5; however, because of the forward location of the pivot, the wing area also increases by about 9 percent as the panels are rotated forward. This configuration uses a canard as a trimmer and as a means for balancing the airplane to avoid stability changes with changes in sweep angle. The longitudinal control is at the rear of the wing and ailerons are on the rotating panels. This design is conceived as having four engines, of which two are in each of the pods below the wing junctures. An alternate variable-sweep configuration of higher aspect ratio (2.5 to 5.4) is shown in figure 6.

In summary, the potential advantages of the more sophisticated forms of variable geometry are so high that serious consideration of their use for supersonic transports is warranted.

VARIABLE GEOMETRY

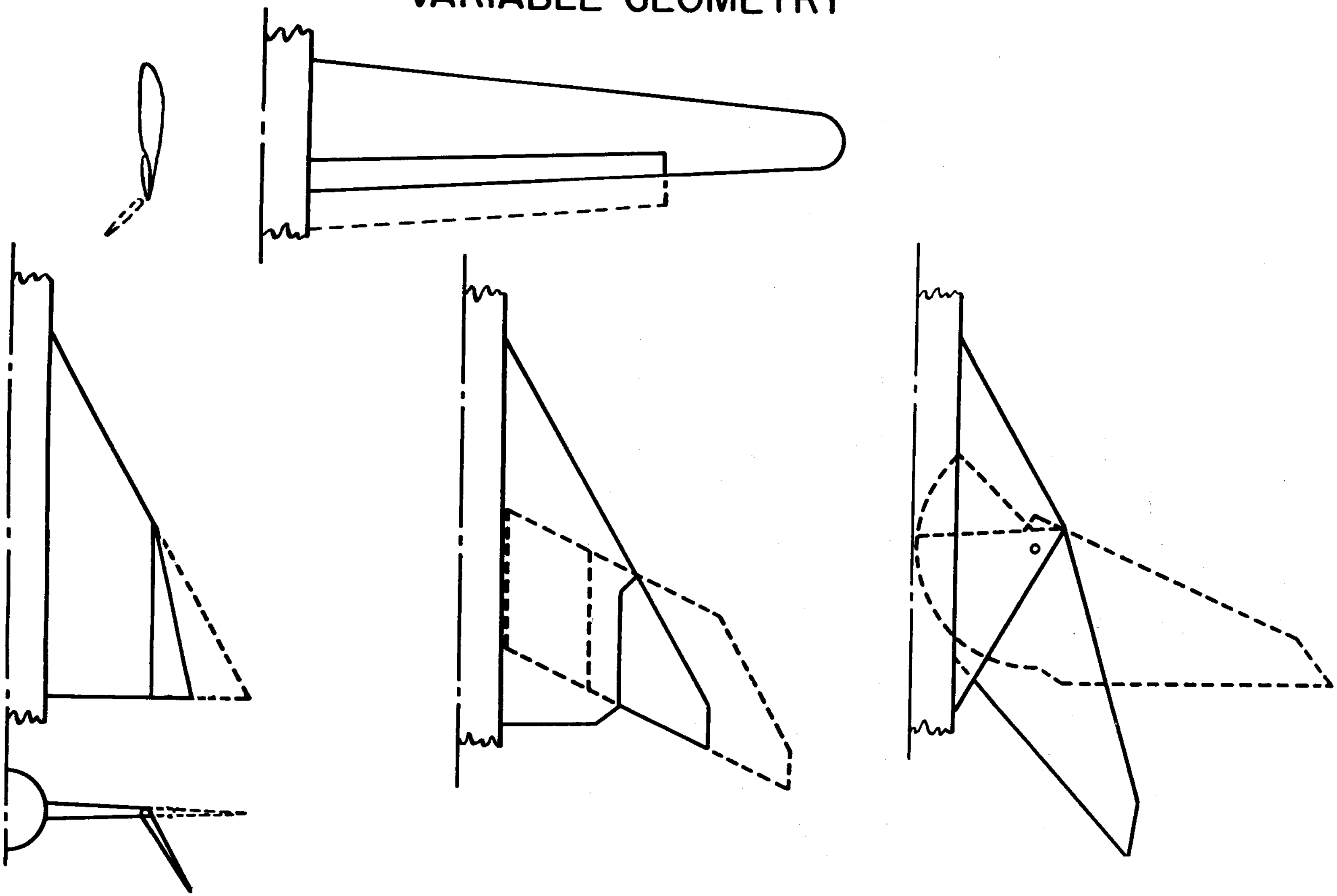
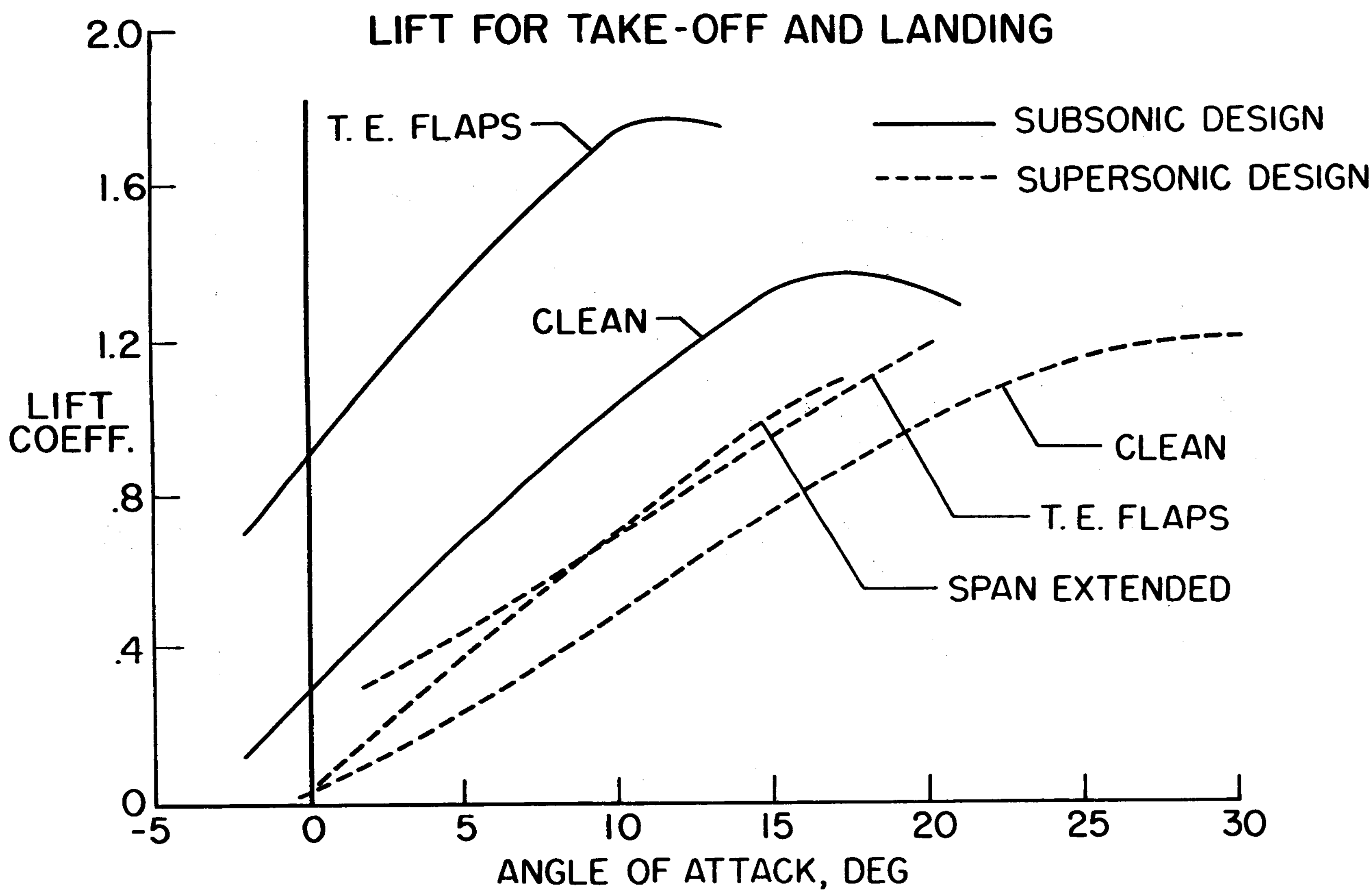


Figure 1



LIFT FOR TAKE-OFF AND LANDING
SUBSONIC DESIGN
SUPERSONIC DESIGN
T. E. FLAPS
CLEAN
CLEAN
T. E. FLAPS
SPAN EXTENDED
LIFT COEFF.
2.0
1.6
1.2
.8
.4
0
-5
0
5
10
15
20
25
30
ANGLE OF ATTACK, DEG

Figure 2

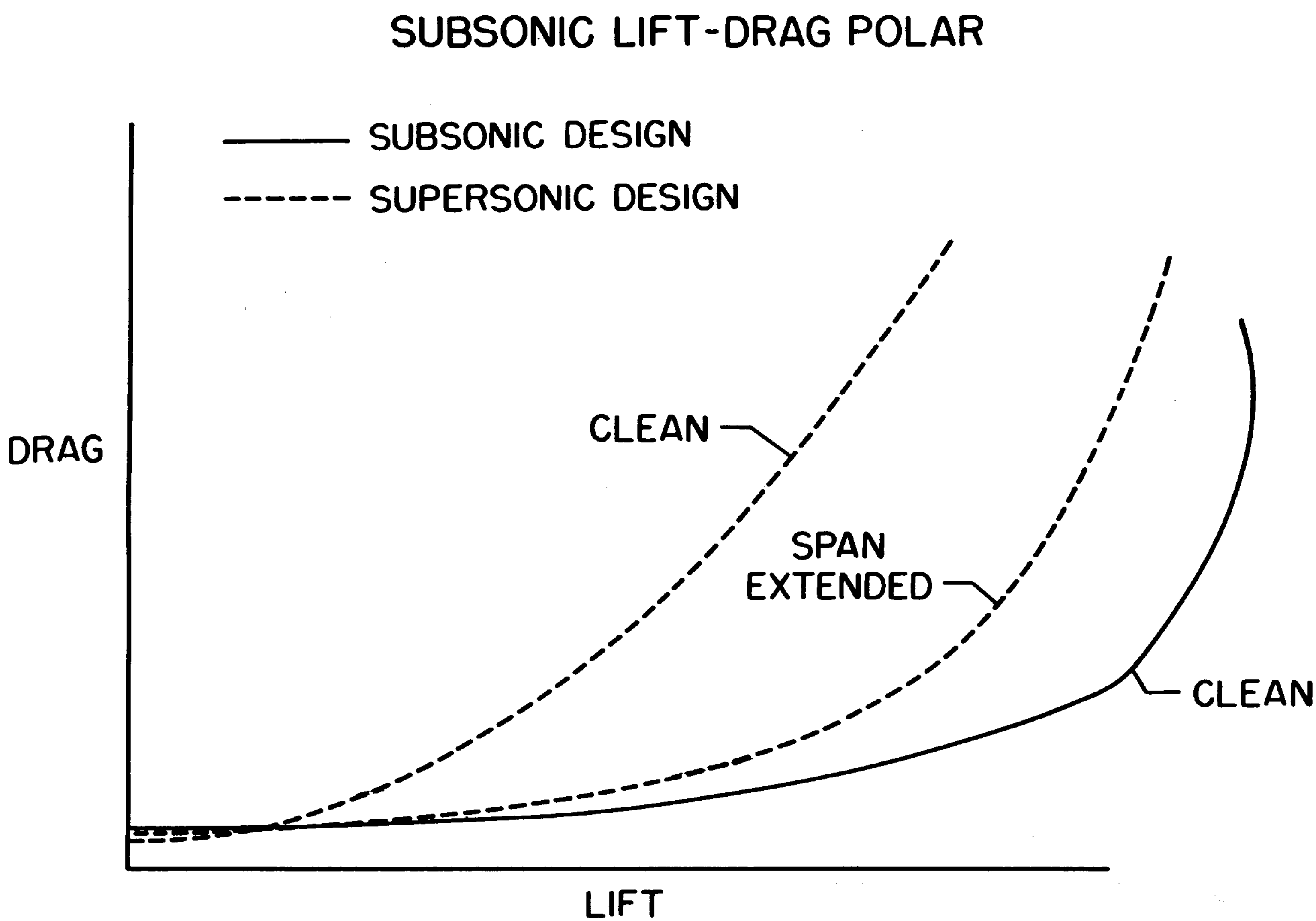

SUBSONIC LIFT-DRAG POLAR
SUBSONIC DESIGN
SUPERSONIC DESIGN
DRAG
CLEAN
SPAN
EXTENDED
CLEAN
LIFT

Figure 3

VARIABLE-SWEEP TRANSPORT

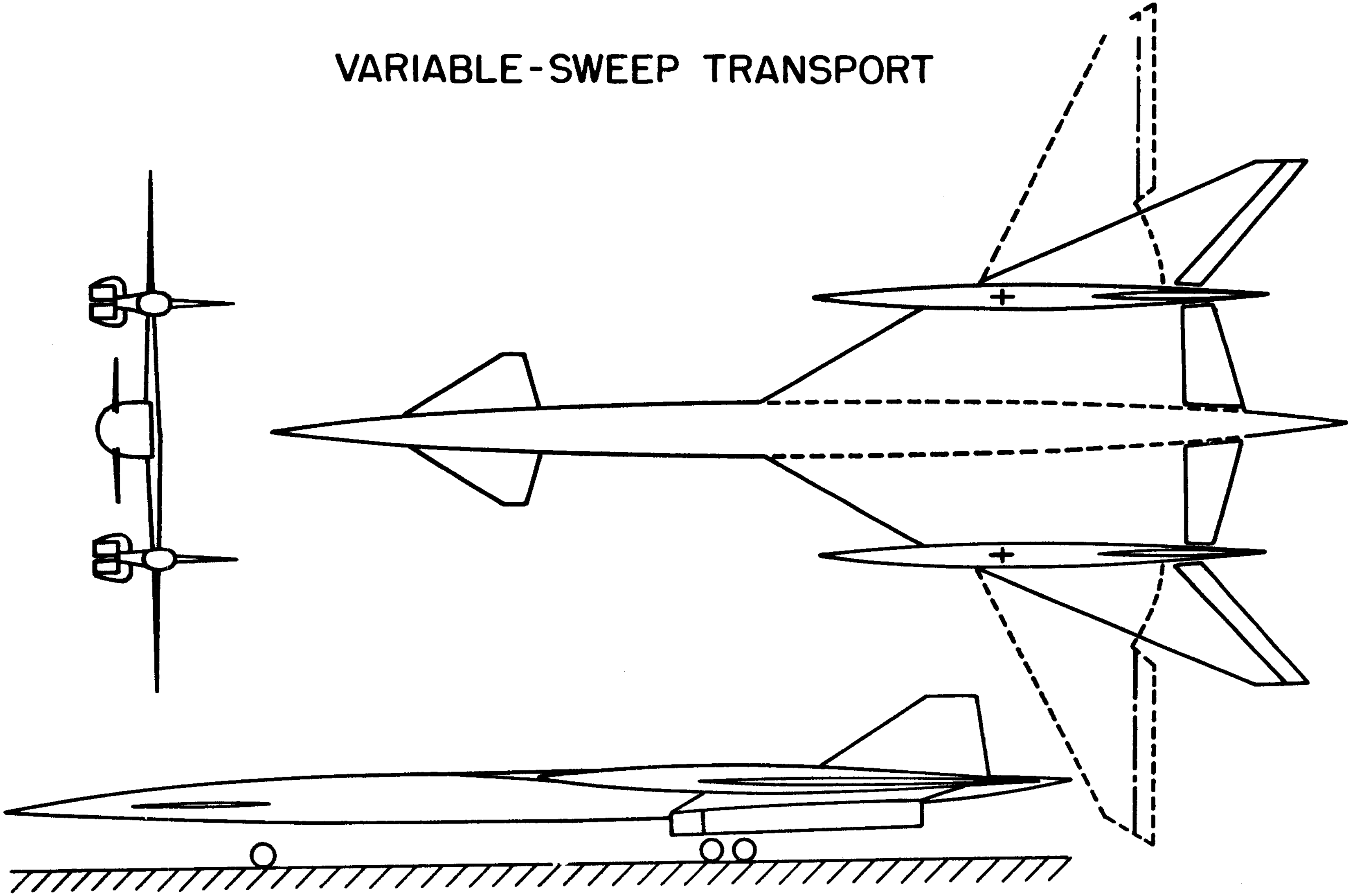
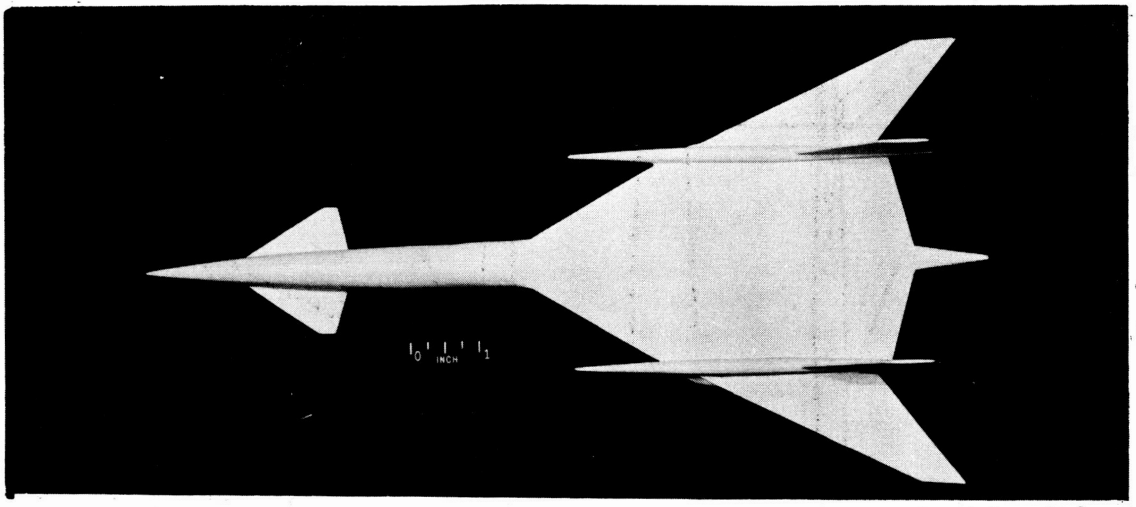
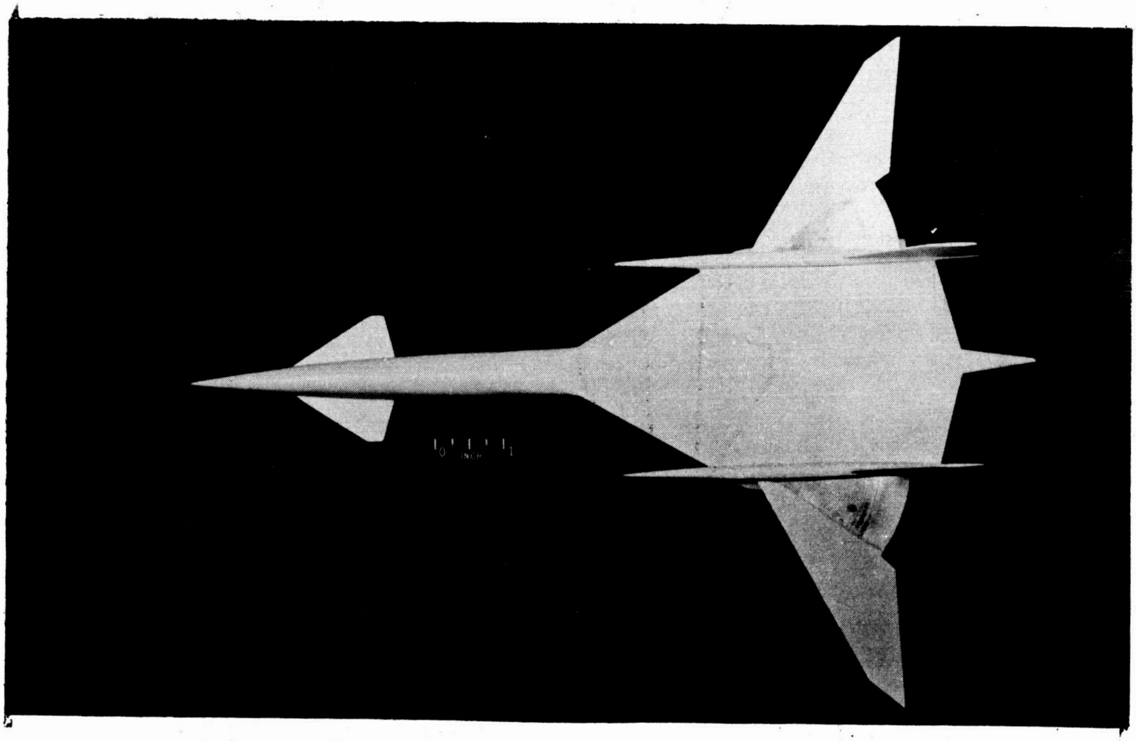


Figure 4

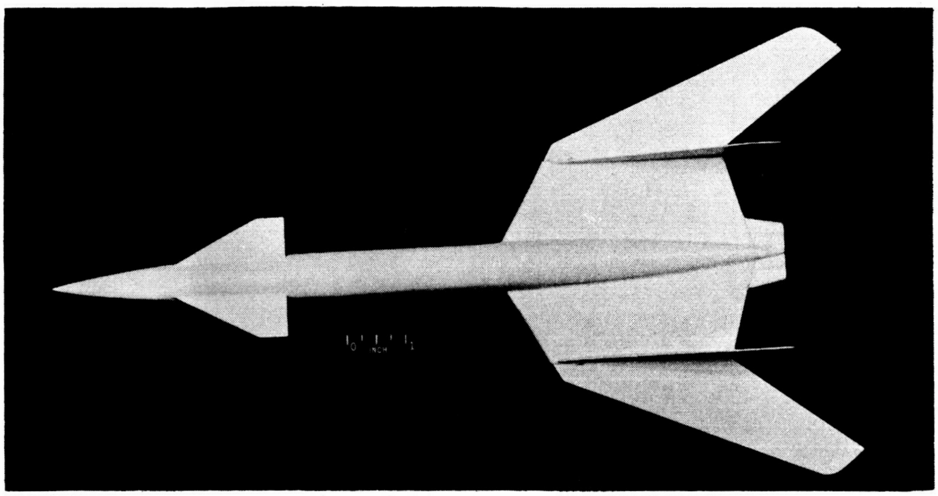


(a) Wings swept. L-59-8573

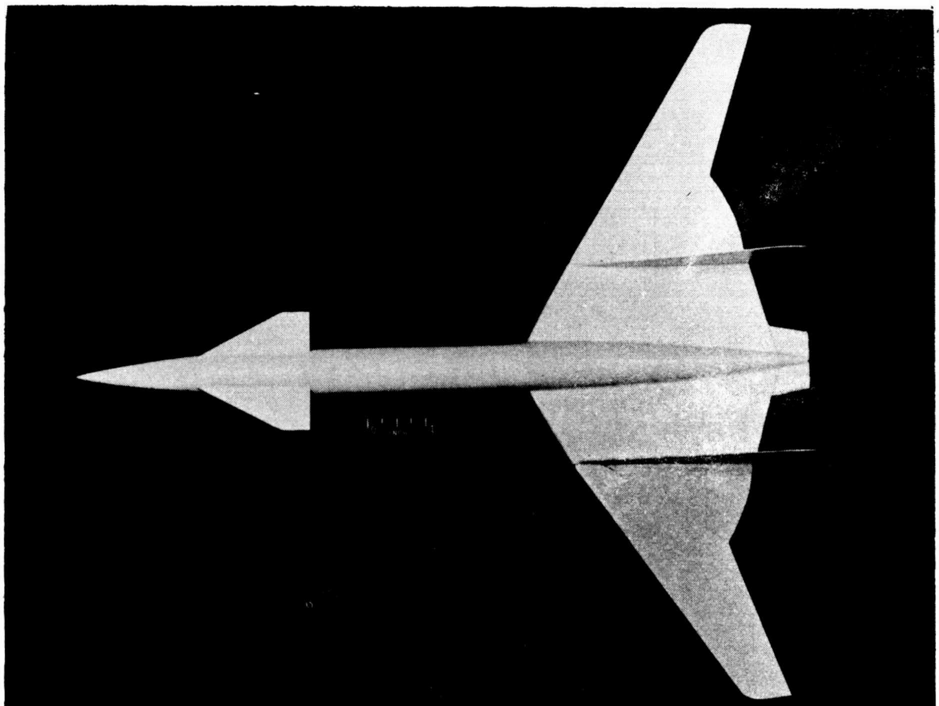


(b) Wings unswept. L-59-8572

Figure 5.- Model of a variable-sweep transport.



(a) Wings swept. L-59-8571



(b) Wings unswept. L-59-8570

Figure 6.- Model of a variable-sweep transport of high aspect ratio.

IX. EFFECT OF VARIABLE SWEEP ON STRUCTURAL WEIGHT

By Eldon E. Mathauser

The effect of variable sweep on structural weight will be reviewed briefly. First, two possible types of mechanical designs shown in figure 1 will be considered. (Leading-edge sweep is varied from 25° to 75°.) These designs include a mechanism labeled as "single point bearing" and another labeled as "concentric track." Photographs of working models of these two configurations are shown as figures 2 and 3. The single point bearing is characterized by a single bearing about which the wing is hinged. This design represents a simple and obvious solution to the problem. The other design utilizing concentric tracks leads to lower structural weight. For one type of aircraft considered, namely a fighter of 58,000 pounds gross take-off weight, the incorporation of variable sweep into the structure (utilizing concentric tracks) produced a weight increase of approximately 3 percent of the gross take-off weight. It is not known whether this same percentage of weight increase will apply to large aircraft of the supersonic transport type. These studies of the effect of variable sweep on structural weight are just beginning and both mechanical designs and weight estimates should be considered as preliminary solutions.

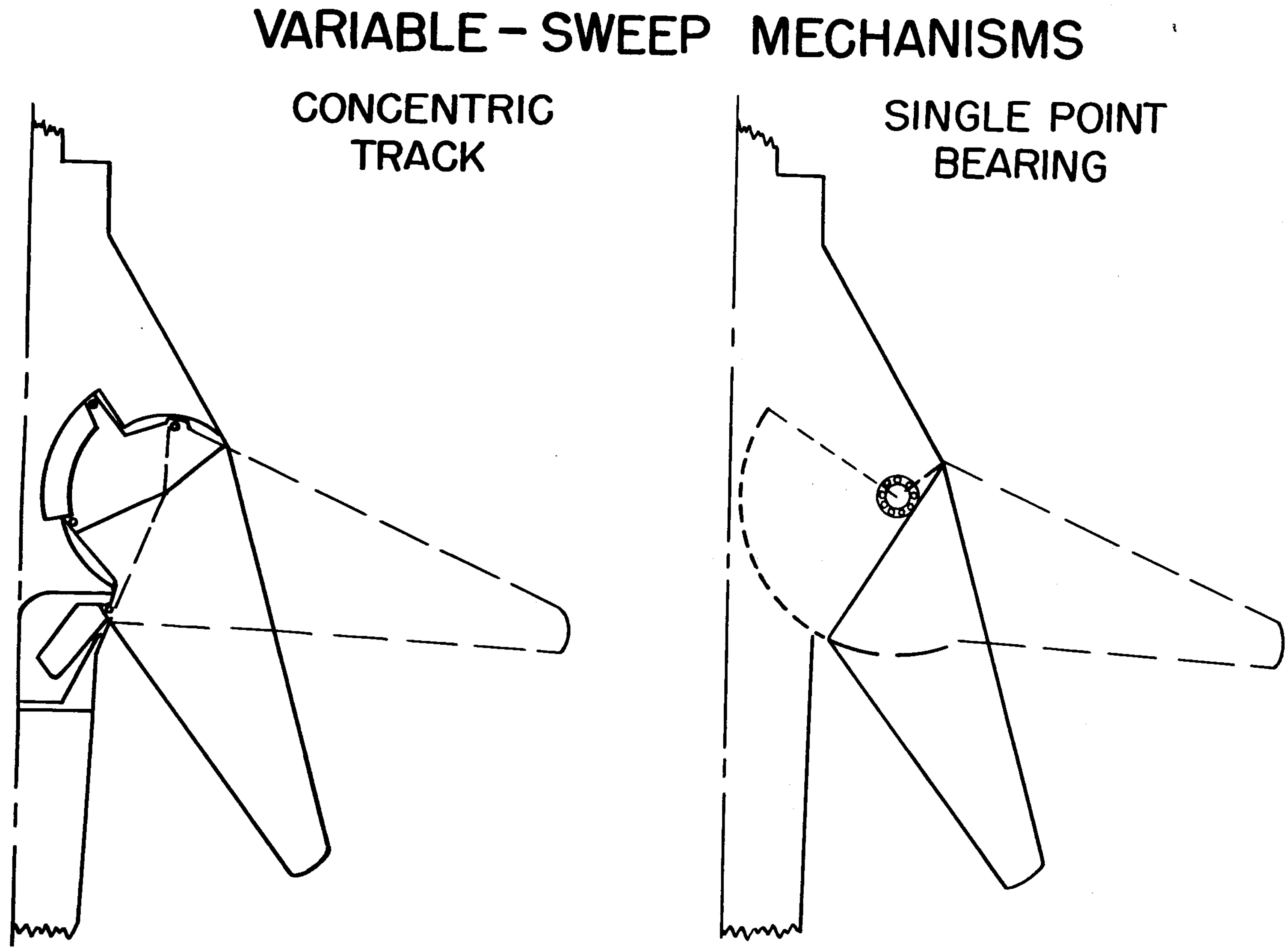
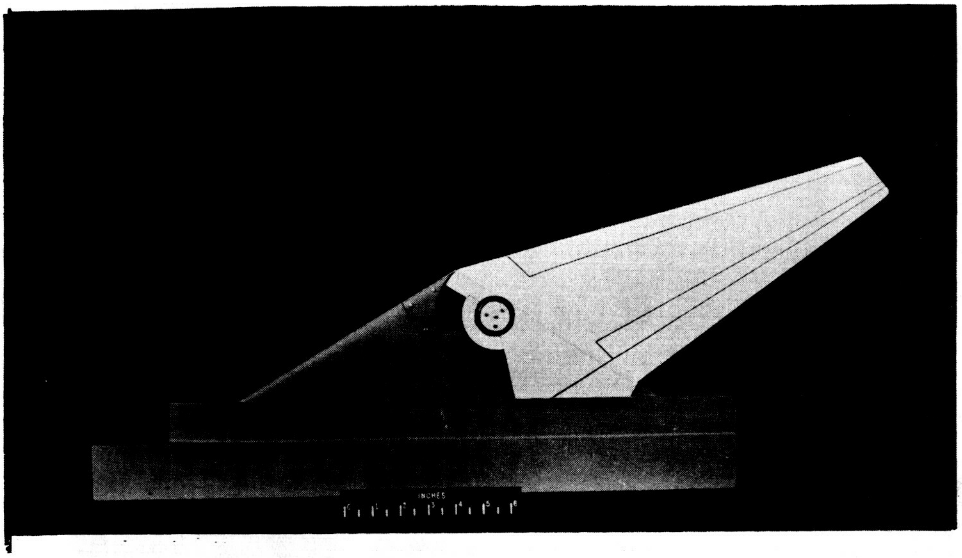
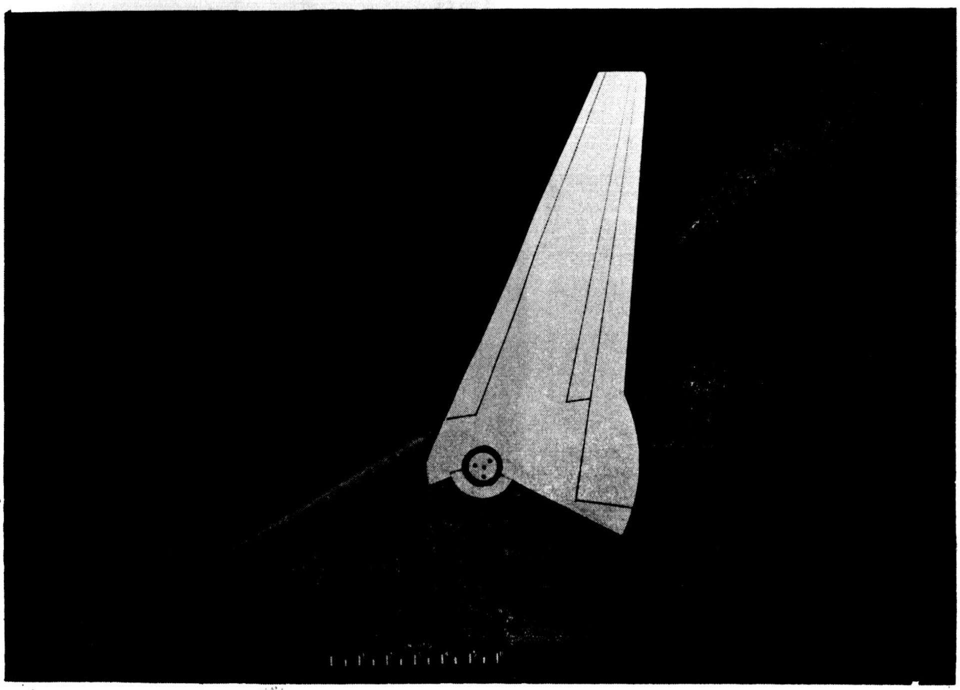

VARIABLE - SWEEP MECHANISMS
CONCENTRIC TRACK
SINGLE POINT BEARING

Figure 1

2A

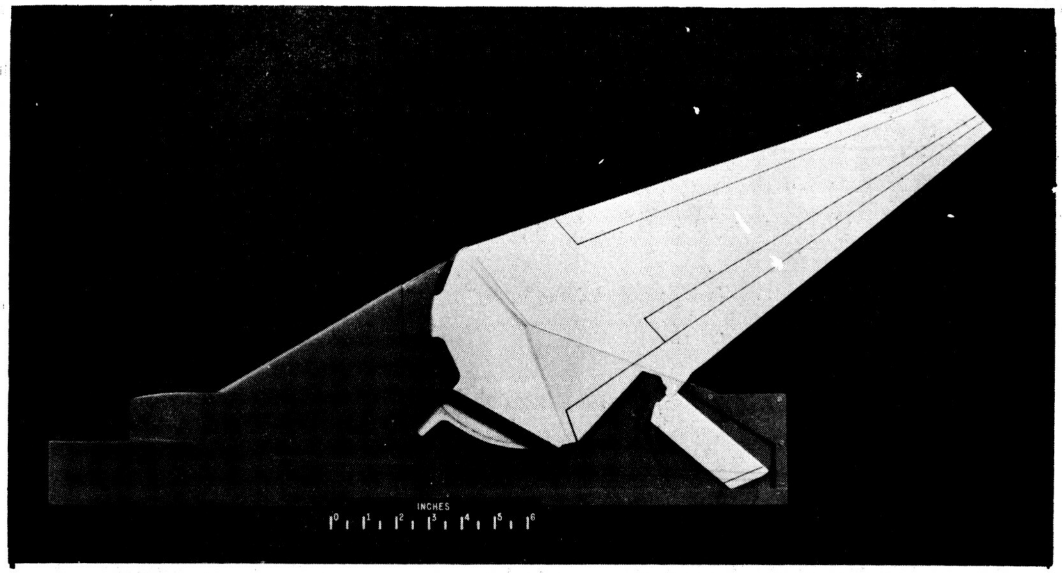


(a) Wing swept. L-59-8558

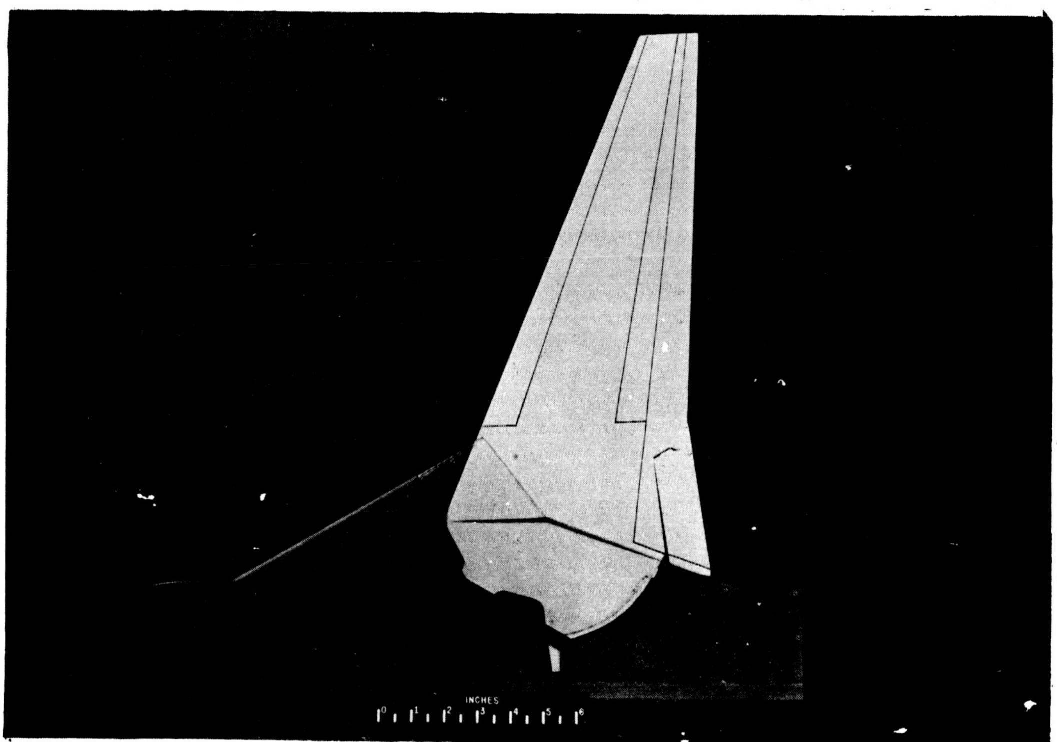


(b) Wing unswept. L-59-8559

Figure 2.- Working model of single point bearing.



(a) Wing swept. L-59-8561



(b) Wing unswept. L-59-8560

Figure 3.- Working model of concentric track.

X. POSSIBLE PERFORMANCE IMPROVEMENTS

By John M. Swihart and Willard E. Foss, Jr.

Ways of improving the off-design performance and operating flexibility of the supersonic transport have been discussed previously in other parts of this volume. Figure 1 shows how the drag of a conventional delta-wing airplane such as that described in part I by Nichols varies with Mach number in the critical take-off, climb, and acceleration phases of flight. The variation of altitude with Mach number shows, for the flight plan considered herein, that the airplane takes off at a Mach number of about 0.3, climbs to 7,500 feet, accelerates at constant altitude to a Mach number of 0.90, climbs at this speed to 35,000 feet, accelerates at constant altitude to a Mach number of 2.0, and then continues to accelerate and climb to the initial cruise altitude of 65,000 feet at a Mach number of 3.0. The solid curve for the plot of drag against Mach number indicates a high drag for the conventional machine during take-off, a decreasing drag level during the subsonic climb and acceleration, and an increase in drag at transonic speeds and during acceleration to a Mach number of 2.0.

It is evident from the dashed curve that the use of variable geometry, such as the variable-sweep concept described by Toll in part VIII, provides a significant performance improvement in the entire subsonic region. Additional performance improvements would be obtained in the holding operation as indicated by the level of the point shown in figure 1.

Table I shows a performance comparison between the conventional delta-wing configuration with four afterburning turbojets and the variable-sweep concept. These data were calculated for standard day conditions using preliminary estimated characteristics without regard for any special Civil Air Regulations. The items considered in the comparison are actual take-off distance over a 50-foot obstacle, touchdown speed at an angle of attack of 12°, the maximum altitude for a 1,000-foot-per-minute rate of climb (really a measure of the fuel cost of the subsonic climb), the percentages of take-off fuel required to perform a 30-minute hold at destination and for an emergency subsonic cruise from midrange as necessitated, perhaps, by a slow depressurization. Significant improvements are shown in each of these important areas for the variable-sweep concept.

Figure 2 shows some of the fundamentals of the airframe-engine matching problem. The shaded region at the bottom is the drag variation with Mach number for the conventional airplane shown in figure 1. The top line represents the thrust performance of a set of four afterburning turbojets matched to the airframe in the usual manner. Maximum afterburning is utilized for take-off, transonic acceleration, and climb to start of cruise, and partial afterburning is used for cruise. Normal rated thrust is used for the subsonic cruise and acceleration. Critical points usually considered in this matching process are take-off thrust, excess thrust available for transonic acceleration, cruise thrust, cruise specific fuel consumption, and fuel consumption for holding operations. It can be seen in figure 2 that these engines are seriously out of match for the sea-level holding operation.

Table II shows some of these critical matching points in detail. A comparison is made of four afterburning (designated A/B) and six nonafterburning turbojet and turbofan engines matched to the same airframe. For this comparison, all engine combinations provide the same take-off thrust, and the airplane gross weights are the same. Items compared are bare engine weight, thrust available for transonic acceleration at 35,000 feet, thrust available for cruise, and the specific fuel consumption at cruise and for sea-level holding.

All values presented in this table are relative to the four afterburning turbojets. The six nonafterburning turbojets are shown to be slightly heavier, provide lower thrust for transonic acceleration and cruise, and have higher specific fuel consumption for holding. Therefore, the airplane would require a higher lift-drag ratio. However, if afterburners were added to some or all of the engines, the thrust for acceleration could be increased as much as 40 percent; and the thrust could be matched for cruise at a relatively slight cost of additional take-off weight. When this is done and two of the engines operate at minimum afterburning for cruise with the remainder at normal rated thrust, the specific fuel consumption is lower by 8 percent. The fuel consumption for sea-level holding could also be made competitive by shutting down two or more of the six engines and running the balance at increased engine power.

It should be stated that the turbofan data presented here are from preliminary designs, whereas the turbojet data just discussed are from engines in hardware development; therefore, these turbofan data are only preliminary estimates. With these items in mind, the data indicate that the four afterburning turbofans with 1:1 bypass ratio are lighter, have more acceleration potential, and provide substantial improvements in subsonic sea-level specific fuel consumption. The six nonafterburning turbofans with 1.75:1 bypass ratio are heavier and provide less acceleration thrust. As much as twice the acceleration thrust could be obtained if afterburning were provided.

The point to be made here is that none of the engines considered possesses all the characteristics desired for all phases of the supersonic transport mission. It appears entirely possible that some new engine - presumably a turbofan with a different bypass ratio - can be developed which will both reduce the take-off noise and provide improved performance and economy over a substantial portion of the mission profile.

In conclusion, it has been shown that substantial improvements in take-off, landing, off-design performance, and operating flexibility may be possible through modifications to airplane design. It has been indicated that research and development on a new engine better suited to the supersonic-transport-flight profile would be desirable.

TABLE I

PERFORMANCE COMPARISON

L
9
4
8

Item	Conventional	Variable sweep
Take-off distance over 50-ft obstacle, ft	9,000	5,000
$V_{touchdown}$ ($\alpha = 12^{\circ}$), knots	150	120
Maximum altitude for 1,000 ft/min rate of climb at $M = 0.9$, ft	35,000	44,000
Take-off fuel (30-min terminal hold), percent	11	7
Take-off fuel (emergency subsonic cruise from midrange), percent	26	20

TABLE II

ENGINE COMPARISON*

Item	Turbojet		Turbofan	
	4 A/B	6 Non A/B	4 A/B	6 Non A/B
Bare engine weight	1.0	1.1	0.85	1.3
Thrust (M = 1 at 35,000 ft)	1.0	0.88 (1.4 - A/B)	1.3	0.73 (2.0 - A/B)
Thrust (M = 3 cruise)	1.0	0.82	1.0	1.2
Specific fuel consumption (M = 3 cruise)	1.0	**4 NRT - 0.90 2$(A/B)_{MIN}$ - .94	0.96	0.95
Specific fuel consumption (sea-level hold)	1.0	1.2	0.55	0.63

*Engine combinations have same take-off thrust values relative to 4 afterburning (A/B) turbojets.

**NRT, normal rated thrust.

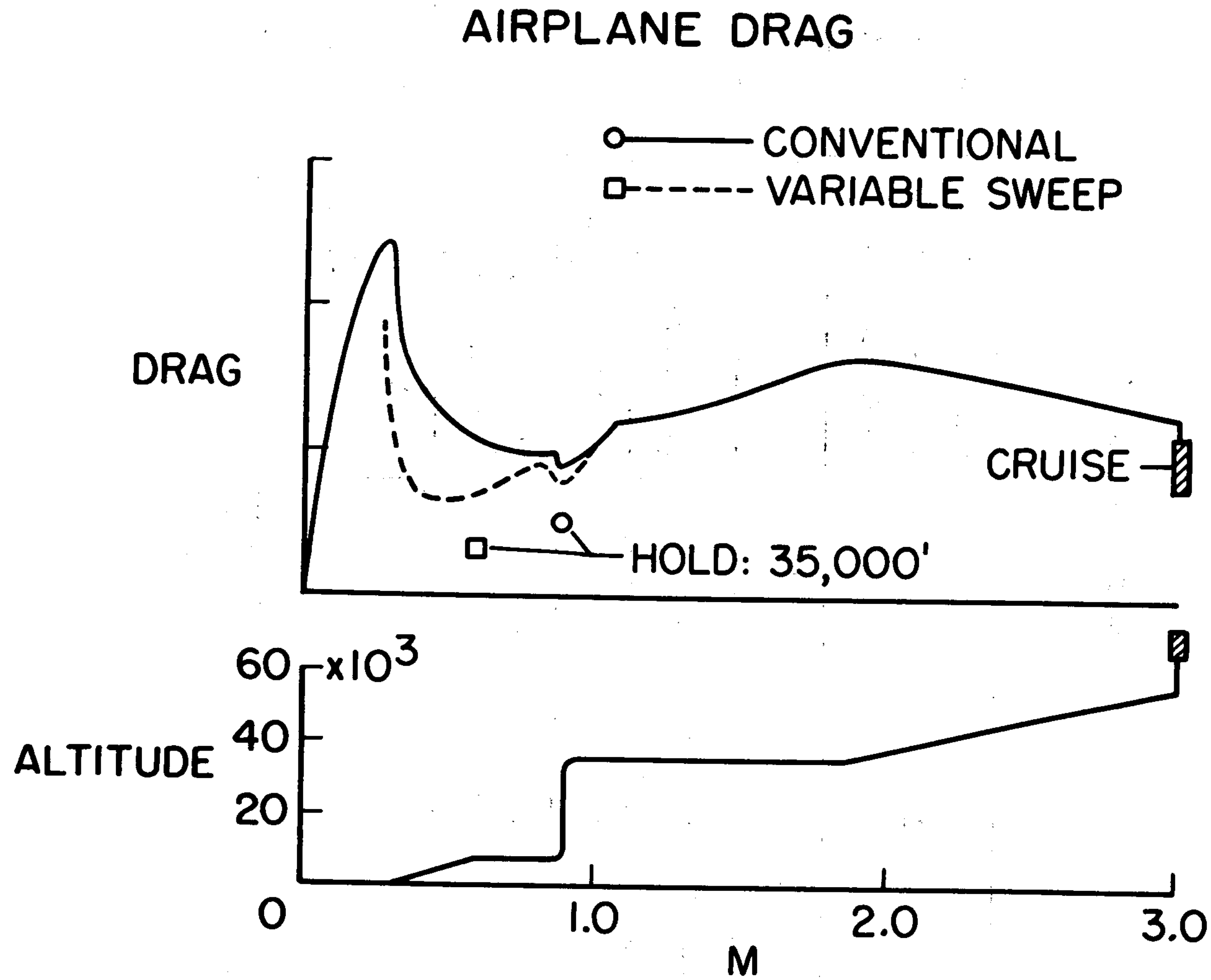

AIRPLANE DRAG
CONVENTIONAL
VARIABLE SWEEP
DRAG
CRUISE
HOLD: 35,000'
ALTITUDE
60
40
20
x10^3
0
1.0
2.0
3.0
M

Figure 1

AIRFRAME-ENGINE MATCHING

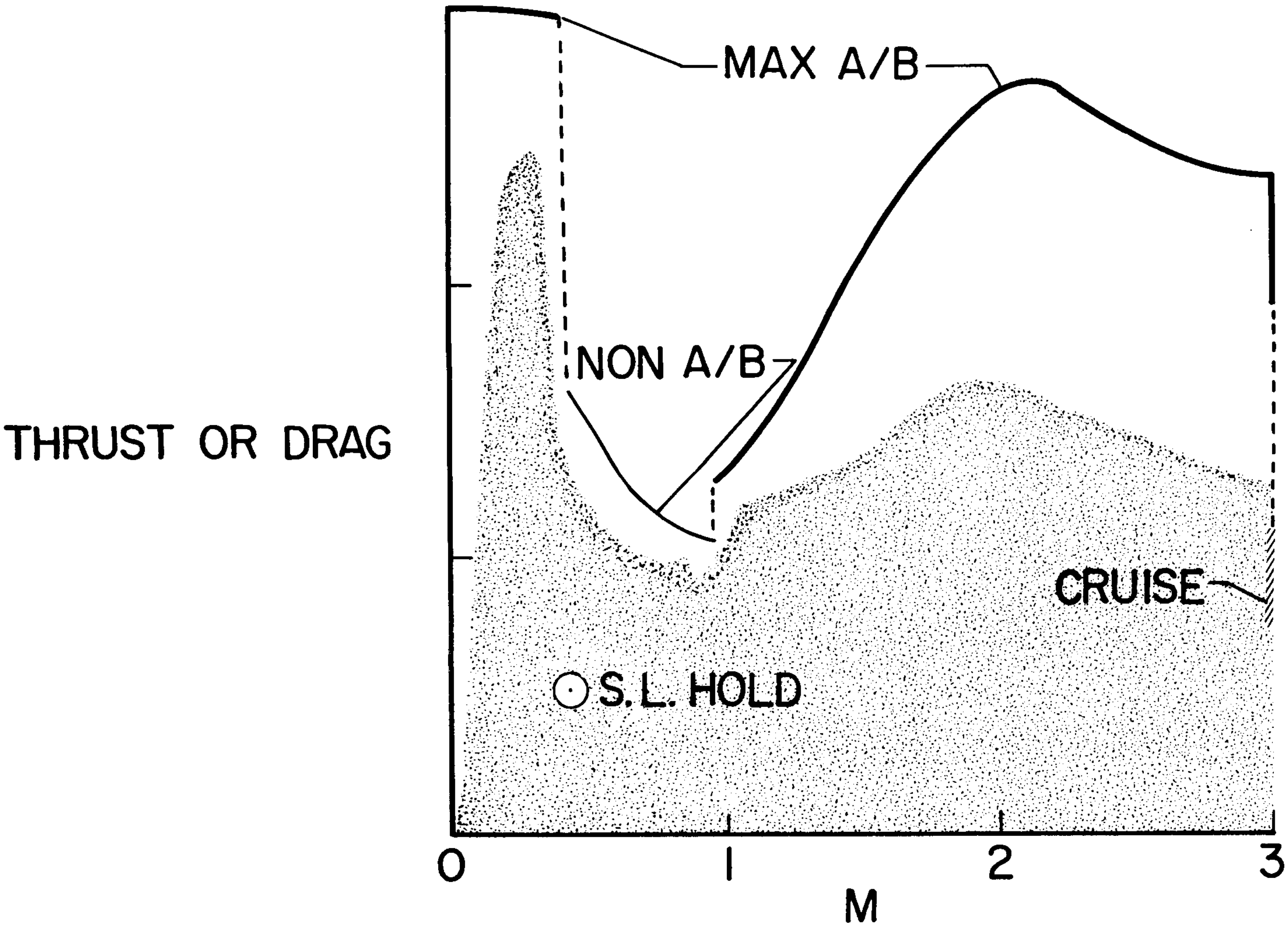


Figure 2

RESUMÉ

Aircraft performance: With regard to performance, the state of the art appears sufficiently advanced to permit the design of an airplane at least marginally capable of performing the supersonic transport mission (3,500 nautical miles). Most designs proposed thus far, however, appear to have serious shortcomings with regard to off-design performance and operating flexibility. Further changes to both the basic airframe and engine configurations appear desirable. Also needed is a system of flight controls and communications sufficient to permit the airplane to fly in an optimum manner at all times.

Noise: The higher thrust-to-weight ratios of supersonic transports result in potential noise problems at take-off because of increased noise power at the source. High temperature afterburning at take-off probably cannot be tolerated; however, the development of turbofan engines should relieve the take-off noise problem. Relative to the sonic boom, there appears to be no problem associated with the high-altitude cruise portion of the flight. The climb and letdown phases are critical, however, and supersonic flight may necessarily be restricted to altitudes above 35,000 feet. This poses a serious airframe and engine matching problem.

Structures and materials: Aircraft structural design and materials selection are critically dependent upon cruise Mach number. A life of 30,000 hours is generally considered as a minimum goal and most of this life will be spent at design temperature. Because of long exposure to design temperature, the use of aluminum-alloy construction is limited to temperatures somewhat below 300° F ($M \approx 2.3$). At higher speeds, stainless steel or titanium alloy will be required. The use of sandwich construction can result in weight savings over conventional skin-stringer construction but at substantially increased cost. A critical problem area is expected to be fatigue (particularly sonic fatigue) at elevated temperatures. Research efforts devoted to evaluation of its significance and understanding are needed.

Structural loads: The design of the supersonic transport will encompass loading conditions more severe than present subsonic transports. Areas needing evaluation and research are those associated with the unknown gust spectrums at high altitudes, gust response characteristics of supersonic configurations, the inability to slow down rapidly, the problem of increased cabin pressure differential, and the higher ground loads resulting from possibly increased landing and take-off speeds.

Handling qualities: Supersonic aircraft are characterized by an increase in longitudinal stability and a decrease in directional stability in going from subsonic to supersonic speeds. These characteristics, combined with the high relative density and greatly differing mass distributions, produce handling qualities significantly different from present jet transports. As a result, automatic damping about all

three axes will probably be required. There exists a critical need for development of configurations with fail-safe characteristics such that in emergency they can be flown on manual control alone.

Runway requirements: The take-off and landing speeds for fixed geometry supersonic transports tend to be higher than current jet transports, but runway requirements will be within the limits of international airports. Inasmuch as present jet aircraft are considered already marginal relative to take-off and landing, basic changes in airframe and engine may be required to provide any significant improvement.

Traffic control and operations: The supersonic transport must follow carefully prescribed climb, cruise, and letdown procedures. In some respects, this airplane is like a projectile, for once launched it must proceed along a precisely controlled flight path with little or no delays and with a large degree of dependence on automatic flight control and stabilization systems. There must be rapid automatic traffic control over the entire route. The capability of the pilot to assume safe manual control is questionable. The problem of fuel reserves is extremely critical, for present requirements can lead to reserve fuel weights greater than the payload.

Variable geometry transport aircraft: Large wing sweep angles and low aspect ratios needed to achieve supersonic performance are not conducive to good low-speed characteristics associated with take-off, subsonic climb, holding in the traffic pattern, and landing. The use of variable geometry appears to have an aerodynamic potential such that savings in fuel reserves alone may more than compensate for increased structural weight. The potential advantages of the more sophisticated forms of variable geometry - such as variable sweep - are so great that their serious consideration for supersonic transports is warranted.

Airframe-engine matching: The problem of airframe-engine match in a supersonic transport is critical because of the wide range of thrust requirements to be met and the need for high efficiency in off-design operation. The use of wing variable geometry can do much to relieve the engine match problem and to improve the off-design performance and operating flexibility. Performance analyses, however, indicate a strong need for a new engine, probably of the turbofan type, to be designed specifically for supersonic transport operation. Such an engine should have high take-off thrust at low noise levels, a large thrust margin for transonic acceleration, and high subsonic (off design) efficiency as well as good performance in the design cruise condition.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 20, 1960.

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